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THESIS

DEVELOPMENT OF A 1/7TH SCALE
FIGHTER UAV FOR FLIGHT RESEARCH

by

Daniel M. Lee

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Thesis Advisor: Richard M. Howard

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A program was initiated to develop a radio-controlled fighter aircraft to be used for supermaneuverability and agility flight research. High angle-of-attack flight testing is a high-risk and very expensive endeavor in manned aircraft, and wind tunnel testing to duplicate dynamic maneuvers is extremely difficult. Another means to conduct agility flight research in a low-cost, low-risk environment has been sought. Construction of a scaled generic Navy Fighter model, to be powered by ducted-fan engines and controlled by radio command, was begun. Also, it was deemed essential to incorporate an emergency recovery system in the aircraft, should control be lost due to radio component failure, Primary flight system malfunction, or departure from controlled flight. A parachute recovery system was designed, constructed, and tested for structural integrity, opening shock dampening, rapid deployment, and desired rate of descent. Work will continue, leading to flight testing of forebody modifications for enhanced control at high angles of attack.

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Development of a 1/7th Scale Fighter UAV for Flight Research

by

Daniel M. Lee
Lieutenant, United States Navy
B.S., United States Naval Academy, 1982

Submitted in partial fulfillment
of the requirements for the degree of

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Author: ______________________
Daniel M. Lee

Approved by: ______________________
Richard M. Howard, Thesis Advisor

____
Eric L. Pagenkopf, Second Reader

____
E. Roberts Wood, Chairman
Department of Aeronautics and Astronautics

ABSTRACT

A program was initiated to develop a radio-controlled fighter aircraft to be used for supermaneuverability and agility flight research. High angle-of-attack flight testing is a high-risk and very expensive endeavor in manned aircraft, and wind tunnel testing to duplicate dynamic maneuvers is extremely difficult. Another means to conduct agility flight research in a low-cost, low-risk environment has been sought. Construction of a scaled generic Navy fighter model, to be powered by ducted-fan engines and controlled by radio command, was begun. Also, it was deemed essential to incorporate an emergency recovery system in the aircraft, should control be lost due to radio component failure, primary flight system malfunction, or departure from controlled flight. A parachute recovery system was designed, constructed, and tested for structural integrity, opening shock dampening, rapid deployment, and desired rate of descent. Work will continue, leading to flight testing of forebody modifications for enhanced control at high angles of attack.

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DEDICATION

This thesis is dedicated to Lieutenant John McClaran. Due to injuries resulting from an ejection of an A-7E, he has lost the use of his legs. Perhaps the future use of Strike RPVs will enable pilots like John to use the skills and tactical knowledge they have acquired while fleet pilots, yet are unable to use in manned aircraft due to physical handicaps. These handicaps would not interfere with their ability to complete the remotely piloted vehicle missions, and at the same time, they could participate in serving in the defense of our nation.

I. INTRODUCTION

"Now launch the Alert-15 Panther, now launch the Alert-15 Panther".

Hal had just finished the mission brief and was in the chow line catching a quick bite to eat when the announcement came over the ship P.A. system. He instinctively left his tray and remarked "Gotta run, that's me".

He dashed up one flight of stairs, inboard two hatches, punched the door combination with one smooth, rehearsed motion and slipped into the secured, darkened compartment.

Hal glanced over at the two men at the console and gave them a thumbs-up, then stepped into the dome. Another sailor passed him his knee-board and headset and closed the hatch behind him.

As Hal settled into the full size cockpit, he methodically flipped on the master video switch and numerous other cockpit systems. The dome brightened as the flight deck came to full visual life through miniature CCD video chips integrated into the aircraft and transmitted via secure data linked to the dome.

Out of his peripheral, Hal suddenly sensed motion as two "brown shirt" flight deck personnel manually towed the 150lb R-21 RPV forward of the #4 wire. The special crew dressed in green flight deck jerseys were off to the right, preparing to start and final the aircraft.

"Panther-21, radio check"

"Loud and clear, ready to start", Hal replied.

"Roger"

The special crew became giants to Hal in the cockpit as they hovered over the RPV. The engine instruments came to life. A rapid but thorough scan of the instruments, followed by take-off checks, resulted in all systems go, so Hal toggled the green light to his crew and catapult officer. He also glanced at his 6-o'clock and mentally noted the A-6E Intruder taxiing onto the catapult launch shuttle, laden with radio beacon homing missiles.

With the turn-up signal, Hal advanced the throttles, checked the engine instruments and flight controls, then looked out for the launch signal from the catapult officer. On signal, Hal released the brakes and started the 150ft deck roll. 25-knots, 30-knots, rotate, 35-knots, positive climb, gear-up, flaps up. Nine minutes had passed since Hal had been in the lunch line.

After the T/O checks were completed, Hal checked in (via the internal ship communication network) with Strike for a hot vector. The R-21 climbed to 500ft AGL, accelerated to Mach 0.9 and refined the heading. Within minutes, Hal could make out the ingress point on the beach. He eased down to 150ft AGL on the miniature laser altimeter.

Once feet dry, Hal masterfully hugged the terrain, using the dips and gullies to mask his arrival. As the R-21 popped over the crest of the ridge, Hal pushed over a negative 6 g's in order to avoid gaining altitude. Once stabilized again, he flipped on the Master Arm and readied the radio beacon equipped darts.

At 11-o'clock, five miles, was the dense and heavily armed enemy garrison. Although the SAM systems, radar controlled AAA and even IR homing missiles would be ineffective against the miniature, fast, and primarily composite R-21, Hal still preferred the element of surprise. His mission was to locate and designate the mobile command headquarters for a stand-off A-6E attack. The mission would be risky and challenging.

After passing over almost the entire garrison, he spied the van at his right 4-o'clock behind a clump of trees, one mile. The R-21 rapidly banked and pulled 20 g's and Hal centered the van in his HUD. He prepared for the level, close-in, manual delivery of the two seven pound darts. Steady, pickle, pull.

"Red-eye, Red-eye"

The BN in the A-6E had already started to receive the radio beacon, and on signal, released the weapons. The two missiles accelerated and refined the track on the signal and within 58 seconds the command truck was hit by the high explosive ordinance.

Meanwhile, deep within the carrier, the Admiral and his staff monitored the numerous video displays, receiving a real-time duplicate of Hal's visual displays. They noted enemy size, location and composition. And they all waited in anticipation for Panther 21's BDA fly-over of the command van.

Hal turned back toward the garrison and observed the weapons impact. Nice shot! But now the element of surprise was no longer on his side. A hand-launched IR missile passed by his port side, having lost the faint IR signal. A few gunners tried their hand at "duck hunting" with manual AAA fire. Hal concentrated on the task at hand, and the close fly-by confirmed a direct hit of the command headquarters. The staff back at the carrier smiled with approval. Then the Admiral quickly gave the command; "Launch the strike package".

The egress and return to the carrier was uneventful, and all that was left for Hal to complete of the mission was the carrier landing. With a 35-knot landing speed, and 20 knots over the angle deck, Hal flew a visual approach and easily landed between the round-down and one wire.

After taxiing clear, he checked to ensure his crew were in position, then secured the engines. The crew effortlessly hand parked the RPV, followed by refueling and an ordinance reload. The R-21 had used 3.2 lbs gallons of fuel.

Mission Summary: 1.1 hour flight, two cheap beacon darts and two inexpensive beacon homing missiles expended, heavy hostile fire drawn with no casualties, real time enemy intelligence made available to the Battlegroup Commander, and no friendly lives jeopardized. Plus, from a flight deck manager standpoint, there was minimal impact on the present aircraft carrier configuration and operation. Overall, the mission was very successful.

The intent of introducing this thesis with the above scenario was to motivate interest in the potential advantages of unmanned aircraft in support of manned aircraft combat missions. Currently, there are several non-lethal unmanned air vehicle (UAV) programs, but very limited progress has been realized in utilizing UAVs in lethal missions as a force multiplier.

With state of the art technology, the above futuristic scenario is both conceivable and achievable. UAVs should be used to support manned aircraft tactical missions, particularly when the threat environment is very hostile and the risk of losing a pilot and an expensive aircraft is too high. Also, with the technological advances in equipment, composites, and structural design, the g-limited man-in-the-loop can become the limiting factor. Certainly, having the cognitive thinking ability of a human at the controls in the aircraft cannot be replaced, but there are times when the risks are too high. Therefore, lethal UAVs should have a place in our overall national defense arsenal.

It is not the intent or within the capabilities of the academic atmosphere at the Naval Postgraduate School to develop and test strike UAVs. However, the field of research UAVs share many of the same concepts and advantages of potential strike UAVs. Development of flight test methods and instrumentation best suited for research UAVs, as well as studying the application of full-scale tactics and technologies to high-performance UAVs, will lead to an understanding of the advantages to be gained by such a strike UAV as described. Therefore, the emphasis of this thesis is on the research vehicle.

II. BACKGROUND

A. DEFINITIONS

It is beneficial at this point to define some key terminology. There has been a notable lack of consistency in this field as it has evolved among authors and activities in using certain terms. For example, what was at one time called a Remotely Piloted Vehicle (RPV) may more accurately have been called a drone. Therefore, for clarity, the following definitions will be followed throughout this text:

- **UAV** - Unmanned Air Vehicle. As the name implies, a human is not physically inside of the vehicle which is operated in the medium of the earth's atmosphere. A UAV can be remotely piloted, pre-programmed, operated autonomously, or a combination of these three.

- **RPV** - Remotely Piloted Vehicle. A vehicle which is operated by a pilot from a remote station. RPVs can include underwater, ground, or air vehicles.

- **Drone** - An unmanned air vehicle which is pre-programmed to conduct a specified mission.

B. HISTORY

The use of UAVs dates back as far as 1917 when the Navy contracted Glenn Hammond Curtiss to build an aerial torpedo [Ref. 1:p. 40]. The first true UAV was flown on 3 September 1924 by the British as a target drone. Further developments of UAVs for target drones followed. By the end of World War II, the United States had purchased nearly 14,000 target drone UAVs for the Army and Navy [Ref. 1:p.41].

Although interest dropped in UAVs after the war, three incidents occurred where pilots/crew on surveillance missions were downed, which rekindled the interest. By 1965, it was estimated that over 3435 UAV sorties had been flown in Southeast Asia, used in "photo reconnaissance, electronic intelligence gathering, bomb damage assessment, psychological warfare and electronic warfare" [Ref. 1:p. 41]. The use of UAVs obviously negated the possibility of loss of the pilot through capture or death.

More recently, the Israelis integrated UAVs with manned aircraft in tactical combat in the early 1970's in the Arab-Israeli War [Ref. 1:p. 41] and in the Bekaa Valley conflict of 1982 [Ref. 2:p. 24]. One use was to overload the enemy air defense. Also, UAVs which were able to electronically mimic tactical aircraft were sent in, triggering the Syrians to launch SAMs, thereby giving away the site locations, firing parameters and the surface-to-air missile envelopes to high flying reconnaissance aircraft. This method also enabled manned strike aircraft to follow and destroy the enemy air defense. The UAVs were also used for near-real-time reconnaissance through optical and electrical sensor information sent back via digital data link. It was realized that the UAVs were "virtually immune" to hostile fire due to their small size and low IR signature [Ref. 1:p. 41]. UAVs allowed for manned aircraft to remain clear of the modern air defense [Ref. 3:p. 1.1].

Parker also hypothesized that during the U.S.- Lebanon engagement in 1984 that the gun fire would have been more effective had RPVs been used to spot hits. And had the gun fire been more effective, the use of manned strike aircraft could have been avoided as well as the resulting downed aircraft [Ref. 1:p. 43].

Therefore, although UAV developments have not been as spirited and robust as manned aircraft advancements, history has shown a definite interest, value, and need for UAVs in tactical operations. And as will be shown below, recent interest has also been shown for the use of UAVs in aerodynamic research.

C. PRESENT AND FUTURE APPLICATIONS

1. Present Applications

There are basically three separate UAV categories: Non-Lethal, Lethal, and Research. For all three categories, there are several advantages of the use of UAVs over manned aircraft which include no pilot risk, low cost, the use of less fuel, and no requirement for environmental and emergency ejection systems. Additionally, UAVs in tactical missions can fly over other nations with less risk of political ramifications, do not require forward bases, and can reduce manpower losses [Ref. 4:p. 68].

There are numerous examples of UAV programs currently in use or development. An excellent summary is provided in *International Defense Review* for both the European programs [Ref. 5] and the United States programs [Ref. 6]. In order to portray the level of current interest in the use of UAVs for tactical missions and research, the following summary is provided, including some technical specifications (where available).

a. *European UAV Programs*

(1). United Kingdom: In order to meet surveillance, target acquisition, reconnaissance, artillery fire refinement and mine observation requirements, the following UAVs are of interest to the British [Ref. 5:p. 449-457]:

- *PHOENIX*: 160kg gross weight, power by a 19kw two-cylinder, two-stroke engine. Capable of 6h endurance and 50km range beyond the FEBA. Pneumatic catapult launched. Real-time data link of thermal camera imagery. Composite construction. On-board digital flight control computer capable of auto-navigation. Parachute recovery. Can be fitted with synthetic aperture radar, laser designator, sub-munitions dispenser and communication relay equipment.

- *SPRITE*: Helicopter design using counter-rotating rotors. Weighs 40kg and has 2h endurance, 32 km radius of action. With laser altimeter, is useful for very close observation of mines and BDA. Fiber optic data link. Has a low 0.3 square meter radar cross section and has a very low visual and audible signature. Reconnaissance equipment options include a thermal imagery TV, CCD color TV or monochrome low light TV.

- *RAVEN 200*: Fixed wing design, powered by a 12hp two-stroke, two-cylinder engine. Gross weight of 60kg with a 4h endurance and 40km radius of action. Bungee catapult launched, parachute or skid landing recovery. Can carry day or night sensors and transmit imagery.

(2). Federal Republic of Germany: Several reconnaissance and lethal UAVs are being developed or used in Germany [Ref. 5:p. 456]:

- *Canadair/Dornier CL-289*: Built to replace the *CL-89* for surveillance and target-location tasks. Intends to use millimeter-wave sensors with real time data link to improve all-weather capabilities and jam resistance. Is less detectable and should have limited target classification capabilities.

- *KZO/BREVEL*: A real time reconnaissance drone in development.

- *KDH*: An Army lethal combat UAV to be used against tanks and armored artillery, operated deep inside enemy territory. Design calls for autonomous search and destroy capability.

- *DAR*: Similar to the Tacit Rainbow in concept, the lethal UAV DAR will be used to combat and suppress enemy air defenses.

- *GEAMOS/SEAMOS*: A helicopter design with an onboard navigation system. 80km radius of action. It is to be used for both maritime and battlefield reconnaissance and surveillance.

(3). Italy: With the need for battlefield surveillance, target acquisition and artillery fire control, Italy is currently developing four systems [Ref. 5:p. 453]:

- *MIRACH 20:* A miniature RPV equipped with an aerial TV or IR camera. Went into operation in December 1988.

- *MIRACH 26:* To replace the *MIRACH 20*, fitted with more advanced onboard equipment.

- *MIRACH 100*: Powered by a 115kg-thrust turbojet and has been in service since 1984. Used for medium to long range reconnaissance, as an ECM vehicle or a radar decoy, and has a target drone variant.

- *MIRACH 150*: To upgrade the *MIRACH 100* with the target surveillance and acquisition sub-system SORAO.

(4). *France:* With primarily surveillance mission requirements, France has a specialized artillery regiment which uses the Canadair *CL-89* drone, soon to be replaced by the upgraded *CL-289* and the Orchidee system. The two new systems will complement each other. The Orchidee system uses a LCTAR doppler radar for all weather surveillance, has a Zeiss reconnaissance camera and an IR line scanner. The data can be transmitted for near-real time use.

Another system that is being developed with the Germans is the *BREVEL* RPV for improved endurance and range which will be compatible with the Mirage FICA reconnaissance aircraft and the *CL-289* RIVIR stations [Ref. 5:p. 452].

(5). *Switzerland:* The Swiss have a need for border surveillance and they are currently undergoing army troop trials with the *RANGER* UAV [Ref. 5:p. 457].

(6). *Austria:* Also with border surveillance requirements, the Austrian Armed Forces is considering the *DELTAPLAN*. The *DELTAPLAN* is a 80kg vertical takeoff RPV capable of carrying a 30kg payload with an endurance of 2h and radius of action of 180km. A main attraction is the radio controlled precision landing ability, allowing recovery by hand [Ref. 5:p. 457].

<u>European UAV Summary</u>. The Europeans are aggressively developing several UAVs which fall primarily in the 40-250kg (90-550 pound) range. Typical flight regimes for surveillance/reconnaissance UAVs are in the low subsonic range, powered by internal combustion, two-cycle, two-cylinder engines driving propellers. Based on the limited published information on lethal UAVs, it appears small turbojets are required to meet the high subsonic requirements.

b. United States UAV Programs

Management of the UAV/RPV program was consolidated into one branch of the Office of the Secretary of Defense (under the Department of the Navy) after the cancellation of the Army/Lockheed MQM-105 *AQUILA* program in 1987. In order to eliminate redundancy, the Joint Project Office (JPO) was established within the Naval Air Systems Command (NAVAIR) as a coherent cross-service controlling agency for non-lethal UAVs [Ref. 7:p. 17].

According to the UAV-JPO, there are four categories of nonlethal UAVs, defined primarily by radius of action and mission endurance requirements [Ref. 8:p. 4.4.3]:

- Close Range (UAV-CR)
- Short Range (UAV-SR)
- Medium Range (UAV-MR)
- Endurance (UAV-E)

(1). Close Range UAVs: The Army and Marine Corps have a need for a highly mobile system to provide "a view over the next hill", and the Navy has an interest in a "crow's nest" for over-the-horizon capabilities. The specifications of this category of UAV has not been formalized; however, typical systems should have an operational radius of approximately 5-80km [Ref. 8:p. 4.4.3] and 1-6h loiter time [Ref. 9:p. 30]. The Air Force is also interested in the close range systems to provide base security and damage survey of friendly airfields after being attacked. The Canadair *CL-227*, ML Aviation *SPRITE* and the Flight Refueling Ltd. *RAVEN* discussed above are under consideration for U.S. close range needs [Ref. 6:p. 604].

The AeroVironment Inc. *POINTER* is another close range option, which is a 7.6lb backpackable RPV. It is propelled by a battery driven electrical motor, has an 1h endurance and is equipped with a CCD video camera. The system was successfully field tested by the Marine Corps in 1987 [Ref. 10:p. 17] and is currently undergoing a wider review.

(2). Short Range UAVs: The design specifications for the short range requirements were set by the UAV JPO as a 200km range beyond the forward line of our own troops (FLOT) and a 5-12h loiter time. Mission requirements include target designation, communications relay, jamming, weather survey, and gathering nuclear/biological/chemical warfare data [Ref. 9:p. 31]. With the *AQUILA* program canceled, the *PIONEER* and the developing *SKY-EYE R4E-50* systems have been left to fill the short range needs of the different services. The Leading Systems *AMBER* endurance UAV is also being considered for the short range competition [Ref. 6:p. 604].

The *PIONEER* is a 419 pound RPV, propelled by a 26 hp engine driving a pusher propeller, and has a 5-7h endurance capability [Ref. 11:p. 16]. While the system was under baseline deployment on the USS Iowa and with Marine Corps RPV companies in 1987, high success rates of approximately 88% were achieved during the eight month deployment, while demonstrating "continuous real-time reconnaissance, battlefield surveillance, over-the-horizon targeting, naval gunfire/artillery spotting support and battle damage assessment within 100nm" [Ref. 3:p. 1.4]. The *PIONEER* is currently operational with the U.S. Navy and Marines and as of July 1989, had logged 2443 hr and 1316 flights. Most recently, among other missions in support of the Joint Task Force Middle East, the *PIONEER* was used to hunt for mines in the Persian Gulf, using the infrared sensor to detect algae on the mines [Ref. 12:p. 81].

Israel Aircraft Industries is currently developing the *IMPACT* RPV as an upgrade to the *PIONEER*, offering larger payload, longer endurance, and improved reliability and survivability [Ref. 12:p. 49].

(3). Medium Range UAVs: Medium range UAVs will be required to have a 150-700 km radius of action at high subsonic speeds in order to conduct timely high quality reconnaissance imagery in support of strike operations against heavily defended targets [Ref. 8:p. 4.4.3] and weather survey [Ref. 9:p. 31].

Known as the Joint Service Common Airframe Multiple Purpose System (JSCAMPS), the medium range UAV program has awarded a contract to the Teledyne Ryan Aeronautical Company for the *MODEL 350* UAV. The *MODEL 350* can be air launched from attack or fighter aircraft, or be launched from the ground or ship via a ramp. This UAV has a range of 700km beyond the FLOT and is powered by a 970lb thrust turbojet engine. A parachute recovery system is used for landing. The heart of the system is the U.S. Air Force Advanced Tactical Air Reconnaissance System (ATARS), which uses a photoelectric focal plane array and high-rate digital recorder with the ability to transmit real time reconnaissance data. The ATARS also has an electro-optic camera and infrared line scanner [Ref. 6:p 599].

(4). Endurance UAVs: With greater emphasis being placed on short range and medium range UAVs, the endurance requirements have not yet been firmly established by an RFP [Ref. 6:p. 604]. However, a radius of action below 300 km and a loiter capability of up to 36h will be required for communication relays, reconnaissance, target location and gathering weather/NBC data [Ref. 9:p. 31].

The *AMBER* high altitude/long endurance UAV is maturing. The 750 pound *AMBER*, powered by a liquid-cooled, four-stroke, four-cycle, 65hp pusher engine, can carry up to a 300lb payload and should carry an electro-optical surveillance system, a VHF-UHF radio relay and ECM package [Ref. 13:p. 25]. Endurance tests have shown that the *AMBER* UAV can remain airborne between 30-38 hours, dependent on altitude. Efforts are being made to ensure maximum commonality with the *PIONEER* RPV system [Ref. 3:p. 1.7]. Operational tests were scheduled for the fall of 1989 with the Marines [Ref. 12:p. 84].

Another totally autonomous UAV called the *CONDOR*, which incorporates state of the art structural (using an all-bonded composite airframe), propulsion, aerodynamic, and flight control technologies, was flown for the first time in October of 1988. Military applications including reconnaissance, surveillance, target acquisition, BDA, search and rescue, and communications relay. Projected civil applications include drug interdiction, border, highway, powerline, and security patrol, weather data collection, and TV and radio relay. The *CONDOR* has a 200ft wingspan and an aspect ratio of 36.7 [Ref. 14:p. 36].

(5). *Lethal UAVs:* Lethal UAVs do not fall under the management of the JPO, but instead are considered as "missiles" [Ref. 6:p. 604], and are currently under the control of the Joint Tactical Autonomous Weapons System Program Office at the Aeronautical Systems Division at Wright-Patterson AFB [Ref. 15:p. 4].

The Northrop AGM-136 *TACIT RAINBOW* is an example of a lethal UAV, designed as a loitering anti-radiation missile with the objective of cost-effective saturation of enemy air defenses through harassment, confusion, and/or destruction [Ref. 15:p. 4]. The *TOMAHAWK* cruise missile is also, by definition, a UAV.

Development of lethal UAVs is still in infancy or at least the toddler stage, and there is a great deal of potential for growth in this area. Several potential systems are being developed by private industry. It must be noted that lethal UAVs are not intended to replace manned aircraft, but instead to enhance current capabilities or to serve as a force multiplier [Ref. 16:p. 53].

Summary of U.S. UAV programs. With the reorganization and management directives established by Congress in 1987, the overall direction and funding for nonlethal UAVs for the three branches of the armed forces should improve. Each service has specific operational requirements for nonlethal UAVs and timely access to operational systems should result [Ref. 8:p. 4.4.7].

As with the European systems, surveillance and reconnaissance vehicles are typically propeller-driven unless high subsonic speeds are required, necessitating the use of small turbojet engines. There are no lethal UAV systems currently in operation, compared to the few systems in Europe cited above.

c. *Use of UAVs for Research*

There are numerous applications for the use of UAVs in research. As a representative sample, the following current research UAV examples are provided.

At the NASA Langley Research Center, RPVs have been used to determine departure and spin resistance characteristics using a 1/4th-scale radio-control model. Various center of gravity locations and power settings were tested, with no risk to the pilot [Ref. 17:p. 1].

Wind tunnels are very useful in aerodynamics, but there are critical scaling parameters such as Mach number and Reynolds number which can not always be matched. Also, there are dynamic limitations in wind tunnels. UAVs can be very useful in providing an alternative method of gaining aerodynamic data useful for advanced aircraft design. For example, NASA and the Air Force have used UAVs to validate advanced vehicle technologies in the Highly Maneuverable Aircraft Technology (HiMAT) program [Ref. 18:p. 1].

It is speculated that UAVs can be used to validate numerical methods, hypersonic applications and Mach and Reynolds number matching for the next generation of commercial transports [Ref. 19:p. 1].

Work has also been done on the improvement of airfoil sections to be used on UAVs. It was shown that special airfoil sections designed for lower Reynolds numbers (between $3X10^5$ to $1X10^6$) associated with many UAVs provided better performance than full-size airfoils [Ref. 20:p. 1].

2. Future Applications

As technology continues to improve propulsion and structural systems, while the size, weight, and power requirements of electronic components are shrinking, the future is very bright for UAVs. The following ideas are provided as a representative sample of some future applications and engineering challenges in the UAV field.

Smart UAVs are being considered, which could be equipped with artificial intelligence and advanced sensors which would allow them to seek out targets, particularly tactical mobile missiles, fire self-contained ordinance, and return [Ref. 4:p. 72].

A possible tactical scenario was discussed by Skrtic of the LTV Missiles and Electronics Group [Ref. 2:p. 28]. He suggests 6-8 strike UAVs join up with a manned strike aircraft equipped with a UAV controlling computer, and fly formation on the lead aircraft until released for the attack into a hostile environment. The expendable yet accurate, agile UAVs would be exposed to the enemy air defense at a fraction of the cost of even one manned strike aircraft.

Several aerospace companies are privately developing advanced UAVs in both the nonlethal and lethal mission areas. One artist's conception is shown in Figure 1, being carried from a F/A-18 [Ref. 21].

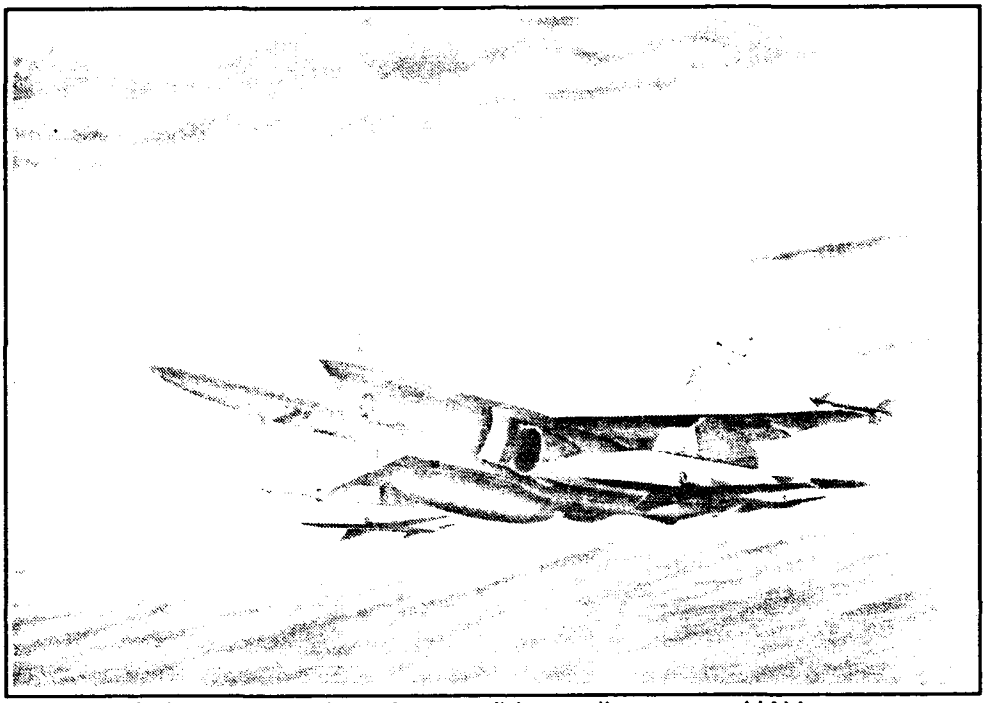

Figure 1 Artist's conception of a possible medium range UAV.

One of the current problems facing UAVs is the complications caused by environmental factors such as smoke, haze, and moisture. Work is currently being done at the MIT Lincoln Laboratory to shrink radar systems to as light as 100 pounds, enabling them to be carried by UAVs, such as the *AMBER* [Ref. 22:p. 69]. Also, the use of synthetic aperture radar in UAVs is being investigated. Both systems would require an accurate inertial navigation system, and it is probable that future UAVs will use the Global Positioning System [Ref. 22:p. 77].

Another inherent concern for UAVs in tactical scenarios is the threat of jamming, of both the control signals and the data-linked information they are providing. Research has been conducted resulting in covert and jam-resistant data communications capability using a microwave data link [Ref. 23:p. 69]. Future research will be needed in this area to ensure mission success in the battlefield.

There are numerous possible uses of UAVs in virtually all mission areas specified for present military aircraft. Parker sites different scenarios where UAVs could be used to supplement manned missions for TARPS. intelligence gathering, Communication, Command and Control (CCC), Anti-Aircraft Warfare (AAW), Surface Search (SSC), War at Sea (WAS), and Strike Warfare missions [Ref. 1:pp. 41-44]. Also, as the war on drugs continues, UAVs could be used cost effectively for drug interdiction.

D. NAVAL POSTGRADUATE SCHOOL UAV PROGRAM

A UAV flight research program has been initiated at the Naval Postgraduate School. A laboratory has been established, with primarily five on-going fixed-wing projects in process, as summarized below.

1. 1/2-Scale *PIONEER* UAV

A 1/2-scale *PIONEER*, originally produced to train U.S. Navy and Marine personnel, was purchased in 1988. This UAV has an 8.2 ft wingspan, 9.0 aspect ratio, wing loading of 3.7lbs/ft^2, and weight of 28 pounds (Figure 2). Power measurements for propulsion performance, wind-tunnel tests in the 3.5-by 5-foot tunnel for investigation of the pusher-propeller configuration, and flight tests have been completed. Currently, instrumentation for angle-of-attack (α), sideslipe angle (β), airspeed, altitude, and control surface positions is being designed, installed and tested in order to determine static stability derivatives.

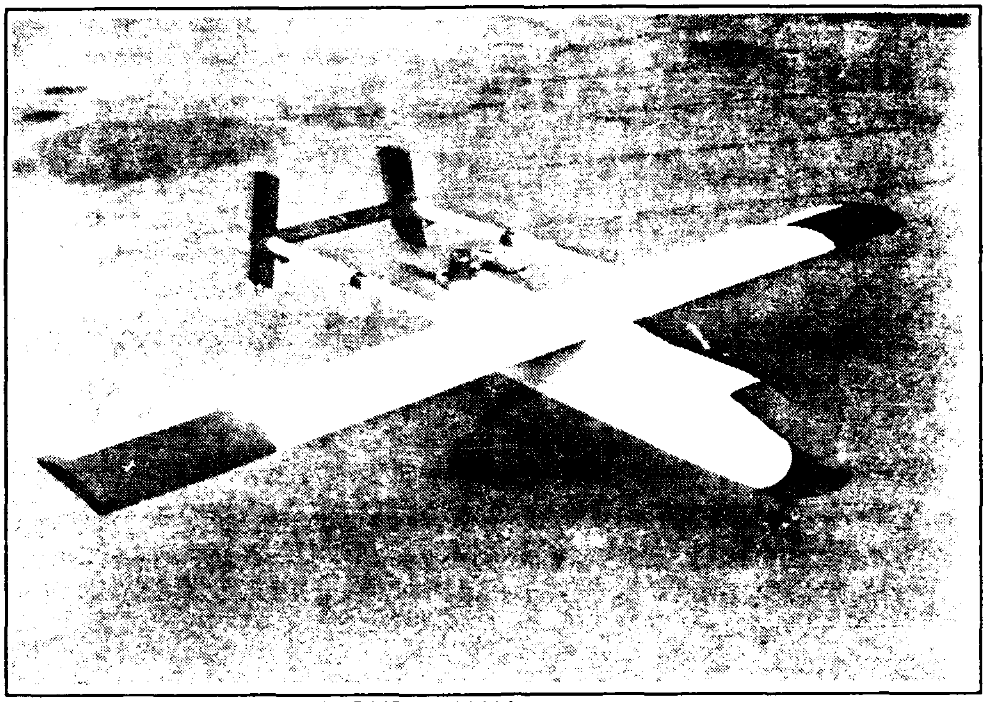

Figure 2 The 1/2-scale *PIONEER* UAV.

2. *ARCHYTAS* TDF UAV

The *ARCHYTAS* is a unique design (Figure 3), conceived and built in the NPGS UAV lab. Construction materials were primarily foam, composites, wood, and aluminum. The vehicle has a 6-foot span and weighs 25 lbs. With a shrouded propeller aft of the wing carry-through spar structure, the aircraft will be used to investigate vertical take-off and associated stability-augmentation technology, forward flight performance trade-offs, and thrust vectoring for yaw, pitch and roll control [Ref. 24:p. 463].

3. 1/8 Scale *F-16* UAV

The F-16 model (Figure 4) has been constructed from a commercially available kit. It weighs 13 pounds and is powered by a single ducted fan. Instrumentation development for airspeed, altitude, engine rpm, α, β, and control surface deflections is currently in progress as well as the design and construction of down-link telemetry. Future

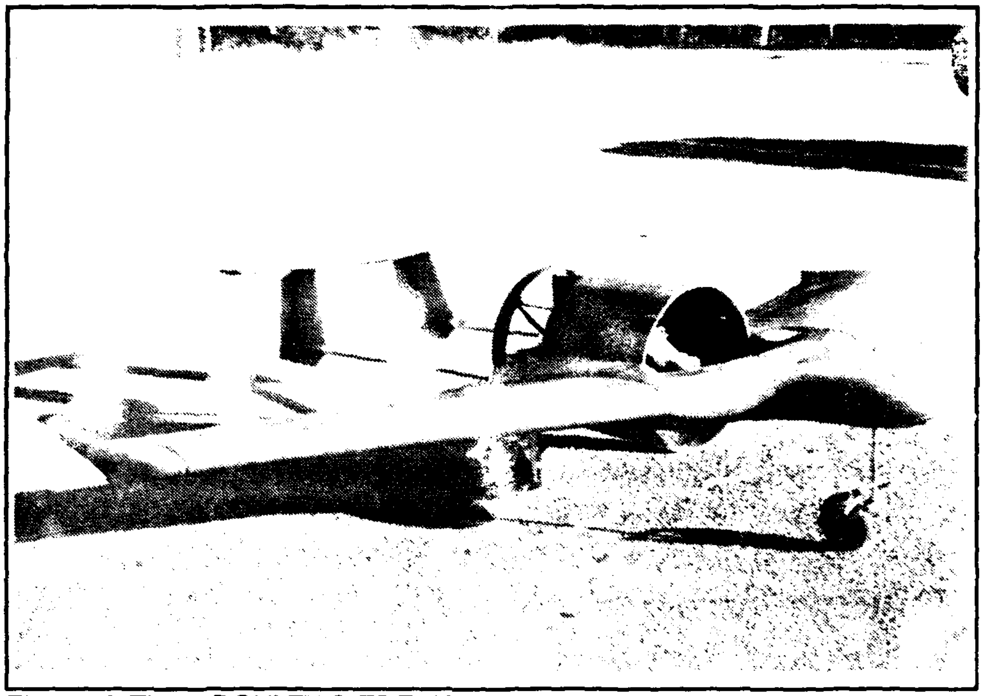

Figure 3 The *ARCHYTAS TDF* UAV.

modifications will be made to investigate agility and supermaneuverability concepts. Weight and size limitations of this model lead to the development of the larger *F-18* model.

A special ground monitoring and recording station is also being designed and manufactured in the UAV lab. Analog meters have been specifically oriented to simulate a "cockpit" type arrangement. The ground recording station has been designed for use with all NPGS UAV flight test projects.

4. *MINI-SNIFFER* UAV

Recently loaned to the Naval Postgraduate School by NASA, this 22-ft span, 170-lb high-altitude, long-endurance UAV will be used to achieve full scale Reynolds number flight tests at low altitude in order to simulate the larger endurance UAVs operated at high altitude.

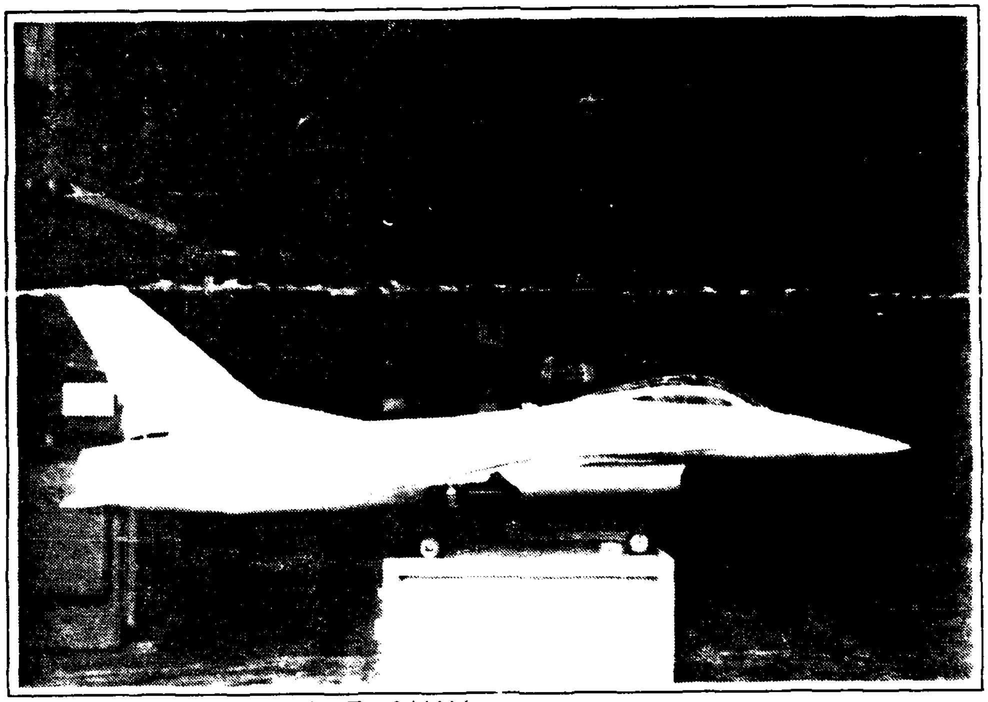

Figure 4 The 1/8th-scale *F-16* UAV.

5. 1/7th Scale *F-18* UAV

This model is the subject of this thesis and will be discussed in detail below.

III. THESIS OBJECTIVES

A. GENERIC FIGHTER UAV RESEARCH VEHICLE DEVELOPMENT

Although the wind tunnel is a very valuable and useful tool in aerodynamic research, there are limitations. Three-dimensional dynamic and high angle-of-attack research requires many difficult corrections to wind tunnel data. While full-scale aircraft are very valuable in flight testing, they are very expensive to instrument, operate, and maintain. Therefore, the use of UAVs as an aerodynamic research tool for flight testing is an attractive alternative.

The primary reason for the development of the F-18 generic fighter UAV is ultimately to complete flight research of supermaneuverability and agility. Once this UAV is completed and thoroughly instrumented, modifications of the aircraft can be done easily and cost effectively to determine the relative value of proposed control enhancements. Although dynamic scaling of the UAV is not applicable, relative improvement can indicate the viability of proposed concepts.

It is not the intent of the UAV flight research facility to design and build lethal or strike UAVs. However, much of the engineering used in the construction and flight testing of the research fighter UAV can be directly applied to the lethal UAV.

B. PARACHUTE RECOVERY SYSTEM FOCUS

The *F-18* UAV was relatively expensive to purchase, will be even more expensive to instrument, and will have a great many man-hours invested in the preparation for useful flight research. Loss of the aircraft due to engine failure, control malfunctions, inadvertent or intentional uncontrolled flight, structural failure, or loss of control signal is not acceptable.

Given the low reliability of model aircraft engines running at very high rpm's and the desire to experiment in inherently risky flight regimes, it was concluded that the additional weight cost for an emergency recovery system was worth the gain of saving the aircraft in the event of an emergency.

Therefore, the primary focus of this project has been the incorporation of an emergency recovery system. The design of aerodynamic decelerators is a complete field in itself. Once a reliable and effective emergency recovery system is developed, the other UAV projects can be modified to include similar systems.

C. OBJECTIVES

To summarize, the objectives of this thesis project were:

- To develop a generic 1/7th scale fighter UAV to be used as a test vehicle for supermaneuverability and agility research.
- To develop a reliable and effective emergency recovery system to save the aircraft in the event of malfunction.

IV. THE 1/7TH SCALE *F-18* PROJECT

A. PROCUREMENT

As part of the UAV research facility overall research goals, the commercially available 1/7th scale *F-18* model was requested in January of 1989. Delays, primarily on the supplier's side, resulted in the model being shipped in parts during the Spring of 1990. Therefore, the project began later than expected.

The model was purchased from Yellow Aircraft at a kit cost of $2000.00, which included most major structural components.

Although the kit came with two ducted-fan engines, it was decided to purchase two larger engines at $295 each, as discussed below in the engine integration section.

Many options were considered for the parachute system, including hand sewing the parachute. Two companies were located which have specialized in making parachute recovery systems for light manned aircraft. Two parachutes and 20 damping systems were purchased at a cost of $195/parachute and $10/web damper.

Many other supplies were needed which had to be purchased separately, including 15 servos, a nine channel radio, two batteries packs, hardware, balsa and plywood, glue, control hinges and hardware, and many other small items.

All together, it is estimated that the model presently has $5000 and 350 man-hours in construction invested.

B. *F-18* UAV SPECIFICATIONS

The *F-18* UAV has a fiberglass fuselage, balsa-sheeted styrofoam wing and tail surfaces, high grade plywood and balsa structural members bonded with epoxy and fiberglass cloth, and aluminum alloy wing spars and landing gear. General aircraft specifications are:

- Length: 9 ft
- Wing-span: 6 ft
- Wing Area: 8.9 ft^2 (with LEX, 9.9 ft^2)
- Aspect Ratio: 3.2
- Wing Loading: 3 lb/ft^2
- Thrust to Weight Ratio (T/W): 0.97
- Maximum Estimated Speed: 150 mph
- Mean Aerodynamic Chord: 1.7 ft (20.4 inches)

The *F-18* UAV, at the present stage of construction, is shown in Figure 5.

C. CONSTRUCTION OF THE *F-18* MODEL

The *F-18* model came complete with most major components and a rough draft set of instructions. Construction generally followed the instructions. A detailed record of procedures used in the construction were recorded in a lab book, which is deposited in the files at the UAV laboratory. The lab book will be used by follow-on students, to insure continuity in the project. A brief summary of the highlights of the construction, particularly where deviations from the plans were necessary, is included below.

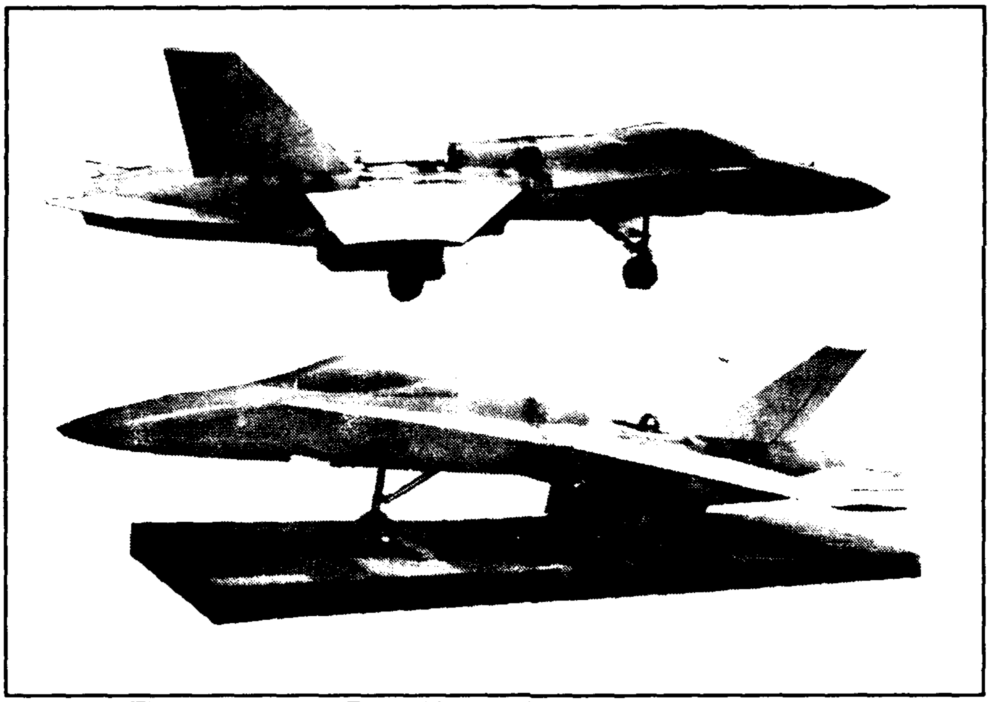

Figure 5 The 1/7th-scale *F-18* UAV, at the current stage.

1. Vertical Tails

Two vertical tails made of balsa covered styrofoam were supplied in the kit. The plans did not call for rudders; however, it was decided that in order to conduct control enhancements and high angle-of-attack research, rudders would be necessary.

Sizing of the rudders was based on the full scale F-18. They were cut out using a razor blade and steel ruler, then trimmed in order to face the exposed styrofoam with balsa. The · ading edge of the rudders were rounded, then center Robart hinges were added (three for each rudder), resulting in ±25° of rudder control (Figure 6).

The rudder control design required the use of only one servo in order to reduce the weight and cost, and to ensure uniform rudder displacement. Two torque rods were formed out of threaded rod and were installed along the leading edges of the rudder (see Figure 6). Holes were cut into the fuselage to pass the torque rods. A servo mount was

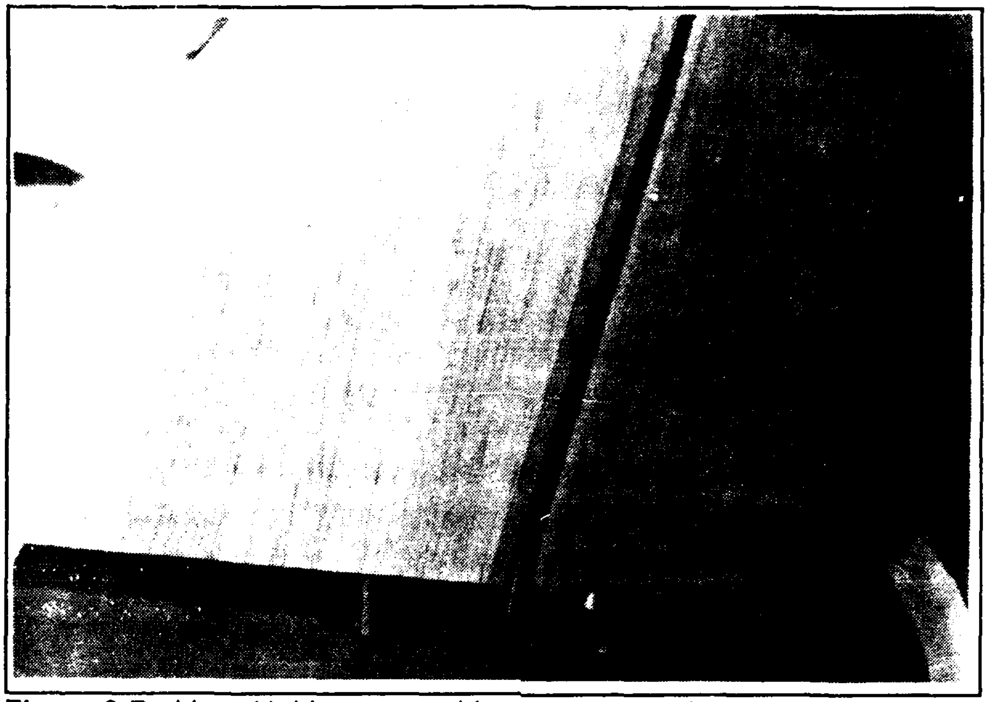

Figure 6 Rudder with hinge assembly and torque rod.

formed out of plywood. The mount extends down from the inside upper fuselage to clear the fixed speed brake door. A single servo arm was used with both rudders connected to push/pull rods via ball/cap adapters. The design has no freeplay, decreasing any tendency for rudder flutter which can become a problem if the control system is not rigid.

2. Wings

The aileron hinge line was pre-cut in the pre-formed, balsa-covered-styrofoam wings, as were the aileron servo compartment and electrical connection tunnel.

The plans did not include flaps, but again it was determined that flaps would be needed for slow flight at high α. The pre-cut aileron line could not be used for the flap hinge line due to the location of the aft wing spar; structural integrity would have been compromised. It was therefore decided to size the flaps down and use a different hinge line. With different hinge lines, separation was required between the flap and aileron longitudinal edges (vice continuous in the full-scale aircraft): otherwise binding of the two control surfaces would have occurred in the both-trailing-edge-down combination of controls. The exposed styrofoam surfaces were faced with balsa and a 1/4-inch strip of balsa was used to anchor the hinges, which can be seen at the bottom of Figure 7.

The additional servo compartment was cut out of the wing along the electrical connection tube at the maximum chord-wise thickness location of each wing (compartment being cut out in Figure 7 to facilitate a totally internal flap control system, decreasing parasite drag. Shafts for the flap control rods we drilled out and a plastic "golden rod" sheath was inserted. Since the flaps would only rotate down, they were hinged at the top and the leading edge tapered to allow for 35° flaps at full deflection. The completed, but unfinished, port wing is shown in Figure 8. During the finishing process, the

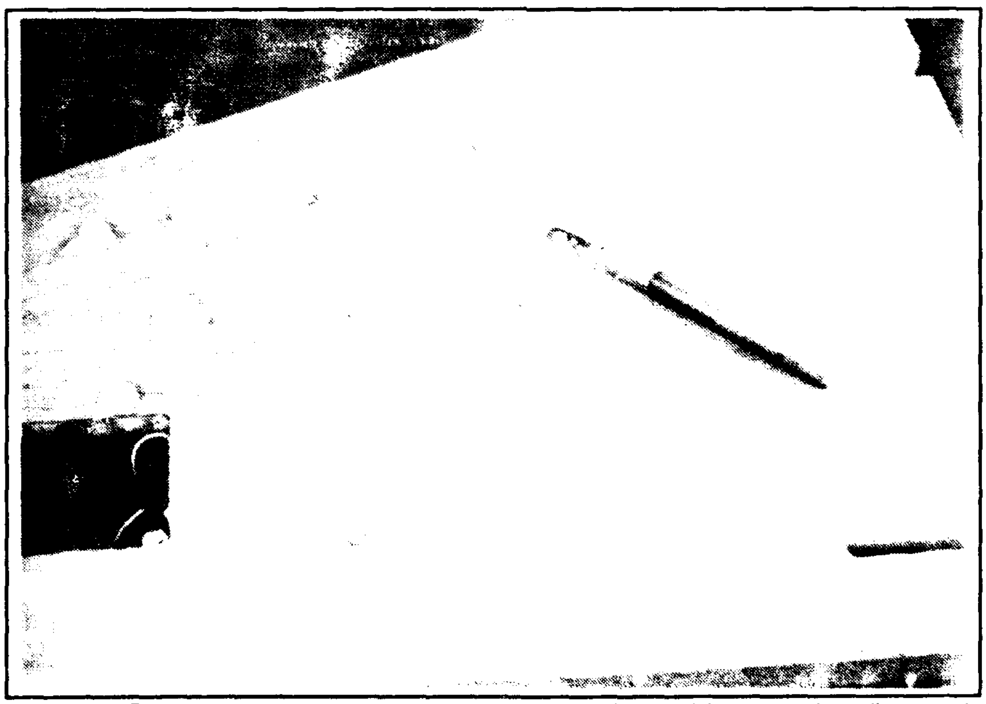

Figure 7 Flap servo compartment and 1/4-inch balsa hinge anchor (bottom).

gap between the flap leading edge and wing will be covered with 1/64-inch plywood, inset and epoxied to the wing. The flexible plywood will ensure a clean and continuous lower surface with less drag.

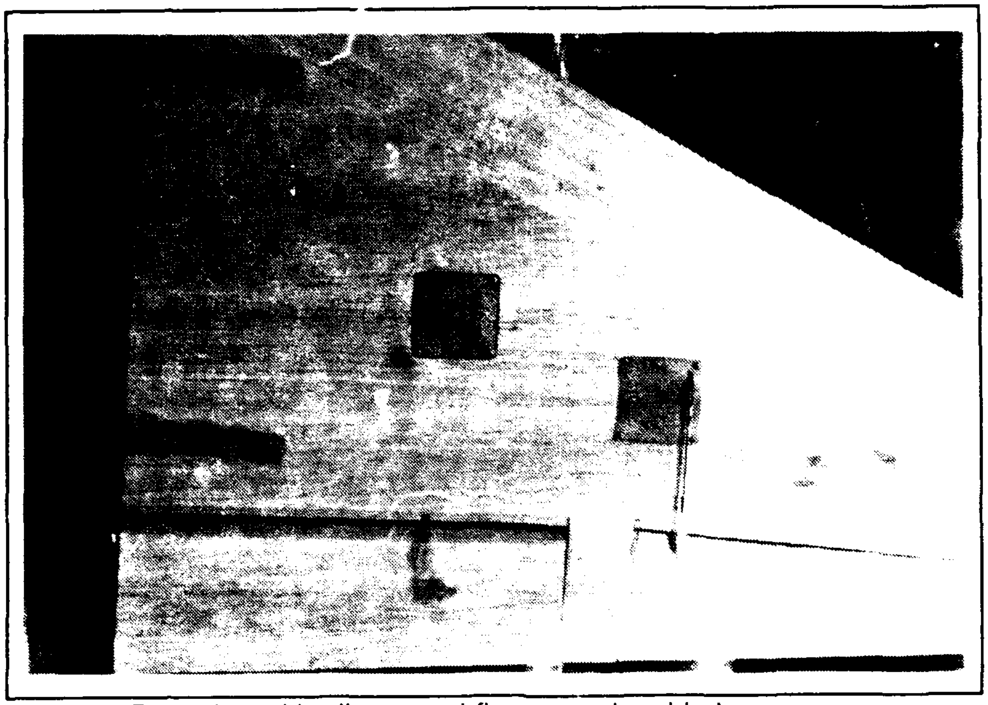

Figure 8 Port wing with aileron and flap controls added.

3. Engine Integration

The kit came with two modified OS-77 ducted-fan engines. Througn initial inspection of the two engines, it was found that the engines differed significantly. The engines had different crankshafts, two of the head bolts had been stripped, and one of the cylinders had been modified internally. In a twin ducted-fan aircraft, and with rpm ranges up to 25,000 rpm, engines matching is critical. Therefore, the engines were not considered acceptable. To date, the supplier has not replaced the engines.

Concurrently, through the advice of several leading ducted-fan hobbyists, it was decided that the slightly larger but more powerful and reliable OS-91 engine should replace the OS-77 engine. Therefore, two OS-91 engines were ordered. It is anticipated that the heads will be too large to fit inside the exhaust ducting, so the heads will need to be milled down and new cooling fins cut for proper engine cooling.

The kit came with two f. ı units, which required assembly. The design incorporated 16 stators and 11 rotors (Figure 9). Within the ducted fan community, it has been speculated that removal of half of the stators improves the net thrust output. Solidity,

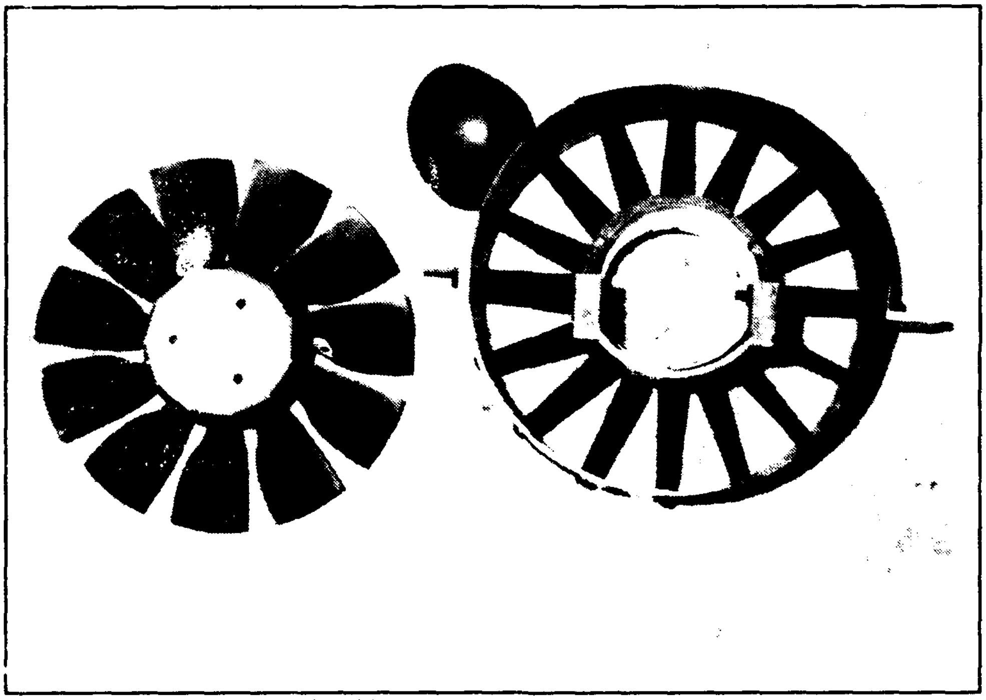

Figure 9 Ducted fan unit with 11 rotors and 16 stators.

turning angles, tip speed, and axial velocity calculations were examined briefly for the rotor and stator combination with Professor Shreeve of the Naval Postgraduate School. It was decided that the most useful way to resolve the ue of the better stator combination was to run static engine tests on a thrust stand. The proposed tests would involve setting up one engine and stock fan/duct assembly on a thrust stand and recording the static thrust output at several stabilized rpm settings. Then every other stator would be removed (by simply removing the single mounting bolt for each stator) and the test would be run again. A plot of rpm verses static thrust in pounds force for the two tests should reveal the better stator combination.

Due to delays in procurement, the engines were not available for testing.

4. Main Landing Gear Integration

The aircraft came with scaled landing gear (Figure 10). The model design required the lower fan mounts be attached to the main landing gear mounts. The difficulty in this design was to get the engines, which were mounted to the fan units, the engine head covers, the exhaust ducts and the main landing gear bases, to fit within the same cross-

Figure 10 Scaled Main Landing Gear.

section of the fuselage and still have the upper hatch and gear doors fit. Also, the alignment of the main gear was critical, necessitating the following three criteria being satisfied concurrently:

- On deck, the aircraft must sit level.
- For taxi, take-off and landing, the longitudinal alignment must be set with no "toe-in" or "toe-out" to ensure proper tracking.
- For retraction, the lateral alignment must be proper to ensure adequate gear door clearance and operation, with proper storage in the wheel well without hitting the exhaust duct.

All of the above criteria were satisfied, but at the expense of the gear door clearance. Great care had been taken to ensure the exhaust ducts provided straight, axial flow with no vertical or lateral thrust components. Once this alignment was achieved, there was not enough room in the wheel well to house the wide foam rubber tires in the retracted position with the gear doors closed. The best option considered was to cut out the gear doors (Figure 11) in the area of interference, then mold fiberglass with epoxy resin to conform to the protruding tires. This procedure will be completed during the finishing process.

The plans called for a servo-actuated gear door retraction and extension system, which would add an additional radio channel requirement and the extra weight of two servos and related hardware. An alternative design was used, where the gear doors were spring loaded to the open position by a rubber band. A system of "strings" was used, which pulls the gear doors closed as the gear retracts (Figure 12). For each door, a light string is anchored to the fuselage on the opposite side of the door opening, and to the inside center of the door. The simple design is remarkably effective.

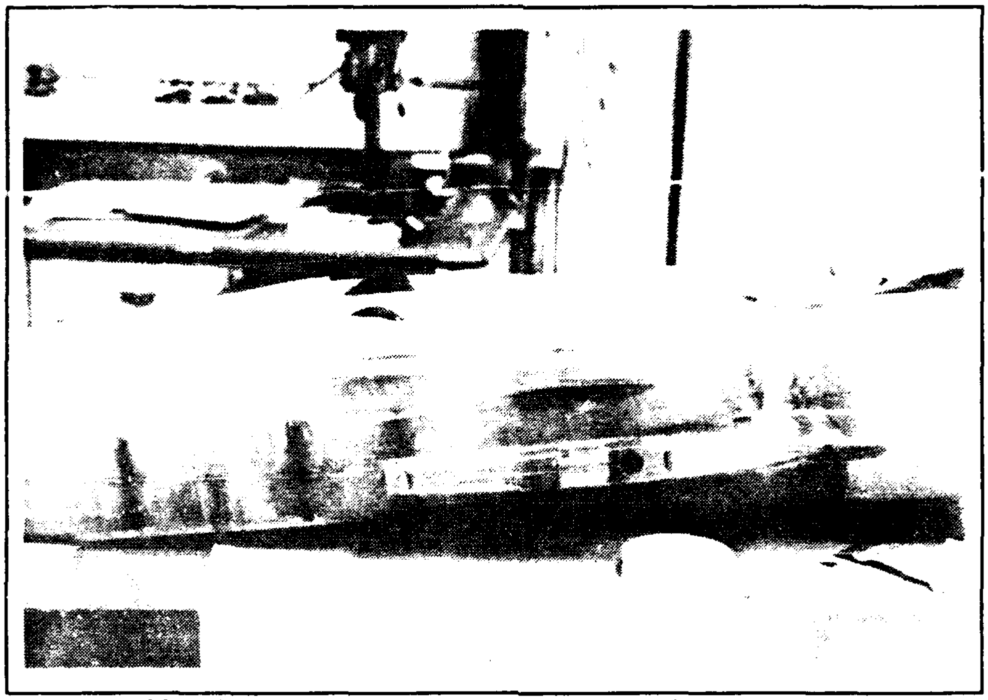

Figure 11 Main landing gear tires protruding through doors.

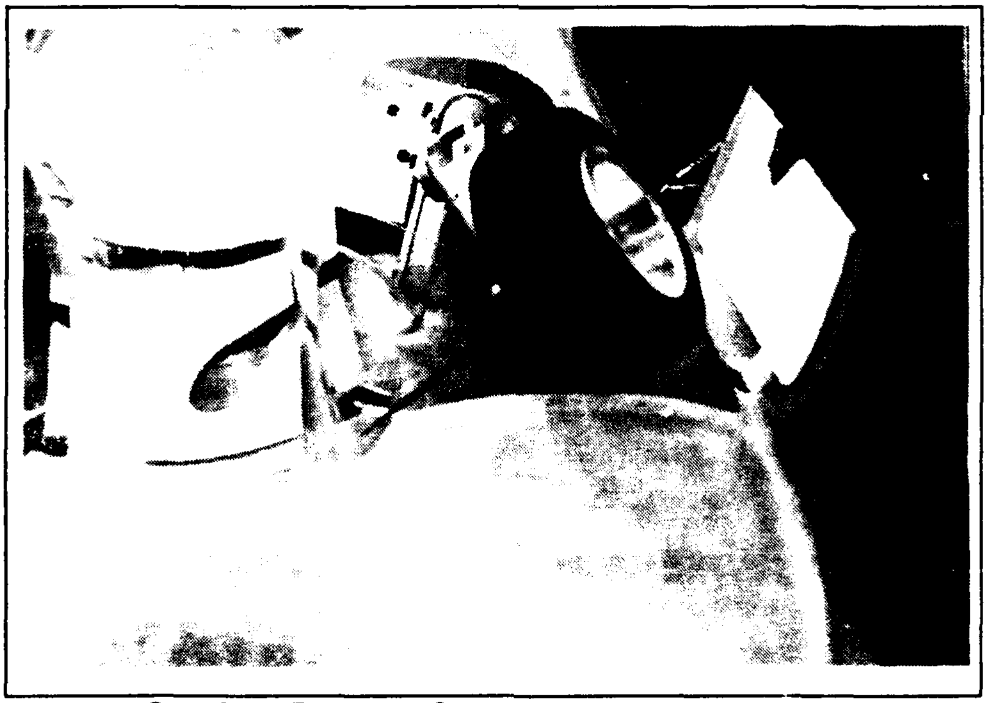

Figure 12 Gear Door Retraction System.

D. PARACHUTE SYSTEM

Aerodynamic decelerators, including parachutes, are a separate and complete field of aerodynamics. Whereas in aircraft design, the engineer is concerned with minimizing drag, the parachute designer is concerned with getting the most drag out of the design, while minimizing opening shock and parachute oscillations on descent. Specifically, the considerations that are important in engineering the emergency recovery system include:

- The size of the parachute is dictated by the maximum weight of the aircraft coupled with the maximum allowable descent rate, which effects the amount of damage the aircraft could sustain on landing.
- The maximum anticipated parachute deployment speed determines the opening shock that the shock damping system and ultimately the airframe must be able to withstand.
- Emergency recovery system deployment method effects the additional weight and space penalties.
- A repackable and reloadable system is desired, preferably at the NPGS UAV lab.

1. Type and Size of Parachute

There are numerous different parachute designs to choose from with a wide variety of coefficients of drag, shape, operating speed envelopes, and descent characteristics. The "Recovery System Design Guide" [Ref. 25] provided by the Defense Technical Information Center is an excellent reference on parachute design that is used by the military as well as industry. For example, there are flat circular, conical, bi-conical, tri-conical, hemispherical, annular, cross, and parabolic parachutes, all with different typical drag coefficients, opening load factors, average oscillation angles and applications. Through the use of this reference, it was decided that the flat circular parachute would serve the design specifications best while being the most economical to purchase and of light weight. For the interested reader, the Appendix contains additional parachute information.

A tradeoff was required between parachute size and weight considerations and the maximum acceptable vertical descent rate. Based on a conversation with an engineer at Ballistic Recovery Systems [Ref. 26], a drag coefficient of C_D = 1.1 is achievable with a zero permeability parachute material and flat circular parachute. Assuming an aircraft weight of 30lb, the required parachute size can be determined from the coefficient of drag formula [Ref. 27:p. 19]:

$$S_p = \frac{Weight}{\frac{1}{2}\rho V^2 C_D} = \frac{30}{.5*.002377*20^2*1.1} = 57.36\ ft^2$$

A good approximation for parachute diameter at full inflation is:

$$S_p = \pi\frac{d^2}{4} : \quad d = \sqrt{4\frac{S_p}{\pi}} = \sqrt{4*\frac{57.37}{3.14159}} = 8.5\ ft$$

Therefore, an 8.5 ft diameter parachute would be required for a 20 ft/s rate of descent.

It was also of interest to determine the weight associated with the parachute system. Historically, it has been found that only 35% of the total system weight is the canopy, while 50% is made up of the lines and an additional 15% for the metal fittings [Ref 27:p. 19]. Therefore, with an 8.5 ft flat circular parachute, with a 1% apex opening, the material area is approximately 60 ft^2 and a material which weighs 1.1 oz/yd, the canopy weight is:

$$W_{canopy} = A_{canopy}\frac{1.1oz}{yd^2}\frac{yd^2}{9ft^2}\frac{lb}{16oz} = 57.36*\frac{1.1}{9*16} = .44\ pounds$$

Based on the assumption of 35% canopy weight, the overall parachute assembly weight should be about 0.44/0.35 = 1.3 pounds. With the addition of the airframe reinforcements and two additional servos, the total emergency recovery system weight is approximately two pounds.

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until thoroughly soaked, and a second 3-ounce fiberglass sheet was added. When dry, the extra canopy was separated, trimmed and sanded to shape.

3. Parachute Deployment Engineering

For an emergency recovery system, the time between initiation to full deployment is very important, particularly at low altitudes. Very fast deployment can be assured with the use of a ballistically fired parachute and ballistic parachute spreader-gun to force a full canopy rapidly. On the other extreme, the parachute can be inserted into the free-stream and deploy aerodynamically. In between, there are many different possible combinations of rocket, mortar, drogue parachute, and spring activated systems. In that the canopy should have good airflow around it in nearly all expected flight attitudes, it was decided to aerodynamically extract the parachute from the canopy housing.

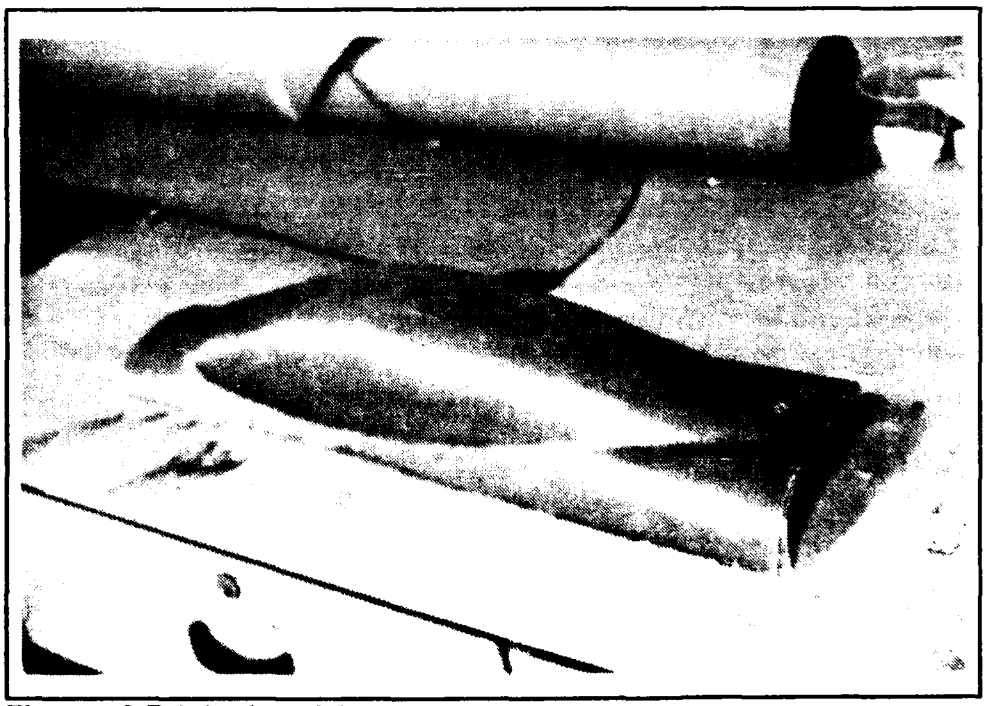


Figure 13 Fabrication of the extra canopy.

The simplest parachute system was decided on, which would be the lightest weight, least expensive, and simplest to integrate, using remote activation, spring initiation, and aerodynamic deployment.

It was desired to secure the canopy to the aircraft solely by the emergency recovery system activation system, while minimizing any drag penalty. The activation system was engineered to have two steel retaining pins, pulled by two servos activated in parallel, from retaining bars mounted internally on the canopy. The servos were mounted inside the upper fuselage forward and aft of the cockpit with the pin motion fore and aft, parallel to the fuselage. Springs were added between the fuselage and canopy in order to ensure positive canopy separation upon initiation (Figures 14 and 15). This arrangement added no additional drag penalty.

Figure 14 Canopy with retaining bars and aft spring.

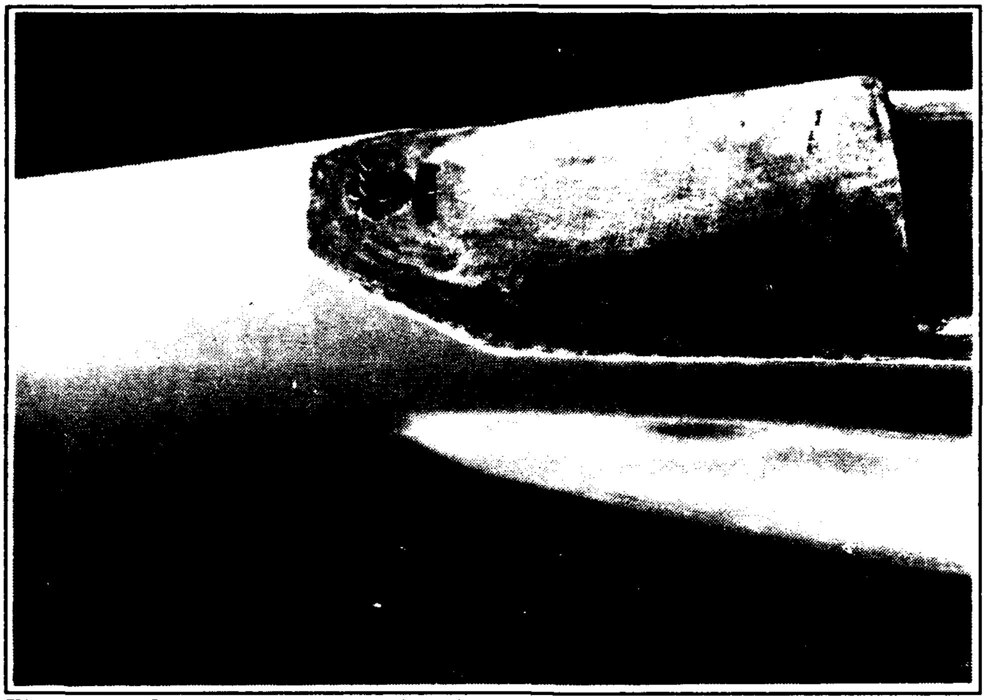


Figure 15 Cockpit with forward spring and retaining pen assemble.

Once the canopy has separated from the fuselage, aerodynamic loads rapidly pull the canopy up and aft. An eyelet was fiberglassed/epoxied into the inside center of the canopy (Figure 14) and a four-foot lanyard joined the canopy to the apex of the parachute. The parachute was housed inside of the cockpit, and as the canopy separates, the parachute unfolds and is extracted by the canopy via the lanyard.

4. Structural Design for Opening Shock

The type of parachute used and the aircraft speed at the time of deployment determine the level of resulting opening shock. Opening loads can be very high. Since the flat circular parachute was selected, an opening shock factor of $C_x=1.8$ had to be designed for (see the Appendix for additional information on opening loads).

The emergency recovery system design limits were set at 60mph and a maximum of 3 g's to be applied to the airframe. The 60mph design specification was decided on as the highest anticipated velocity for high angle-of-attack flight testing. Although the aircraft is capable of speeds up to 150mph, high speed flight is not anticipated.

The 3 g limit was determined as a trade-off between having to purchase a more expensive and heavier parachute producing less opening shock and the additional weight considerations of building up the structural integrity of the aircraft.

With a 60mph velocity design limit, this required a design for an opening shock of (where T_f is a finite-mass parachute-opening deceleration factor) [Ref. 28]:

$$\textit{Opening shock} = C_X * \frac{1}{2}\rho V^2 * W_{A/C} T_f = 1.8 * .5 * .002377 * 88^2 * 30 * 0.35 = 174 \textit{ pounds}$$

Reinforcement of the aircraft to withstand nearly 6 g's was considered unreasonable, so a shock damping system was deemed essential. One of the most effective and least expensive shock dampers is the incremental bridle, or "web damper", which is a long, flat lanyard doubled over and cross stitched with specific thread, depending on the required yield strength. The web damper will start to rip the stitching out when the designed load limit is reached, and dissipates the energy as long as the load exceeds the design limit, until the lanyard is completely extended.

For this application, a 50lb limit was specified, and 20 six-foot web dampers were purchased. Dynamic tests were run on a sample of the web dampers, and a 50lb ±5lb yield strength was achieved [Ref. 28].

In order to withstand the remaining 50lb opening shock, a shock box was designed and integrated into the fuselage. The parachute will be attached to the fuselage at the c.g. location (located at the forward wing-spar bulkhead), via flat lanyard lightly tape to the outside of the fuselage. Since a majority of the weight (approximately 60%) is concentrated in the metal engines, ducted-fan units, main landing gear, and wing assemblies, all in the vicinity of the c.g. position, it was felt that the structural box arrangement was necessary and the additional weight was justified.

The forward bulkhead was reinforced with a 3/36x5/8-inch aluminum spar, fiber-glassed to the bulkhead, engine inlets and fuselage. The parachute is attached to the aluminum spar and forward bulkhead by KEVLAR fibers running through two holes, drilled two inches apart, centrally located in the fuselage (Figure 16). Also, two 1/8x1/2-inch carbon-fiber spars were added to fuse the forward and aft bulkheads together and to transmit the opening load to the upper engine mounts (Figure 17). The load will be transmitted evenly through the forward bulkhead and aluminum spar to the engine inlets

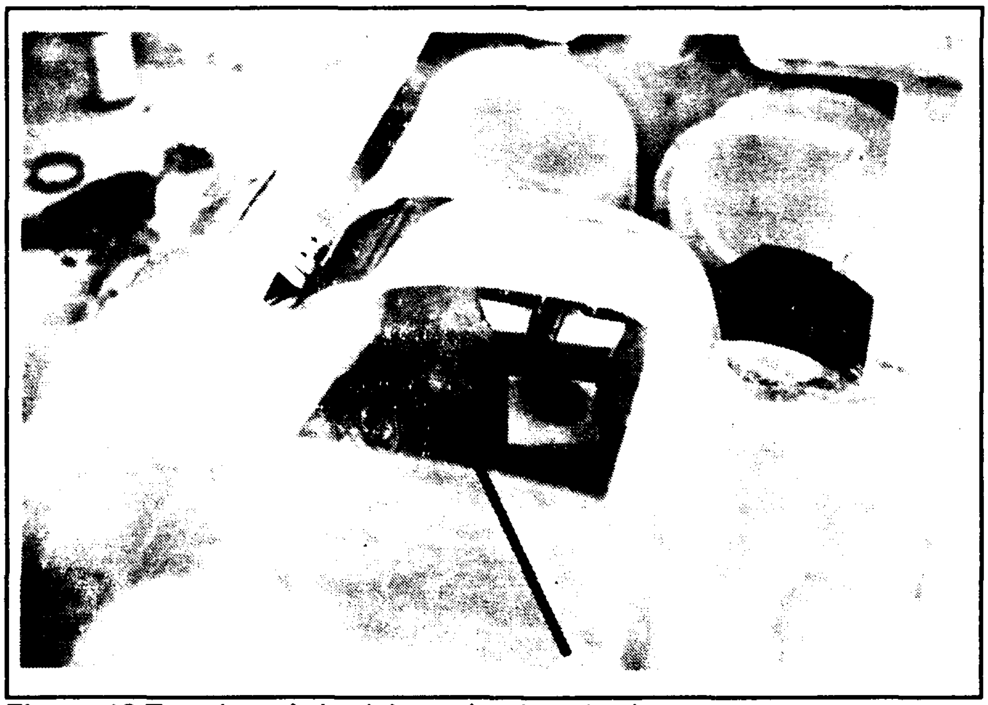


Figure 16 Top view of shock box, showing aluminum spar.

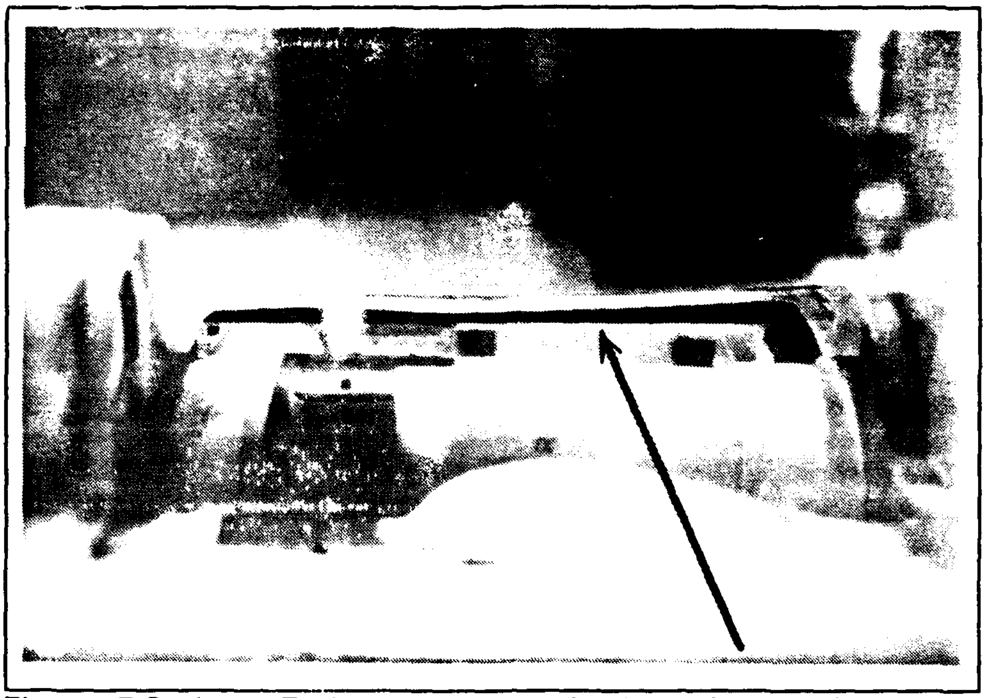


Figure 17 Starboard Engine compartment showing carbon fiber bar.

below, to the upper fan mounts (therefore to the landing gear), to the aft bulkhead and fuselage through the carbon-fiber rods, and to the wings through the aluminum wing spars.

5. Structural Considerations for Landing

The main landing gear and nose gear struts provide minimal shock absorption. A lightweight spring was incorporated within the struts primarily to ensure full extension of the gear for proper retraction into the wheel-wells. With approximately five pounds of weight, the springs are compressed completely. The option of incorporating a viscous damper for shock absorption was considered, but with the oscillatory nature of the flat-circular parachute in a descent, a perfectly level landing was considered unlikely. Therefore, the modification of the landing gear was not justified and it is recommended, if the option exists, to have the landing gear retracted and land the aircraft in grass or dirt in the event of an emergency recovery.

6. Testing of the Emergency Recovery System

The simplest deployment system was decided on. But to ensure that the design would work properly, it was determined that it must be tested. (Had the system not worked, a more expensive and heavier system would have been tested until a reliable and effective system was found.) Wind tunnel testing was not an option, due to the hazards of the ejection of the canopy and the inflation of the parachute. Therefore, it was required to build a forebody dynamic test model which was identical to the *F-18* UAV in size and shape.

Again, using mold release, an epoxy matrix, and fiberglass cloth, the forward 1/3 of the fuselage was reproduced. The process was quite involved. First, the upper 1/3 of the fuselage was molded (Figure 18) in two sections, then the lower section was molded. After the three sections cured, they were pieced together to form a rough forebody section (Figure 19). Through a process of fiberglassing, micro-balloon filling and sanding, the desired shape was formed. After the final shape was refined, the model was painted with a filler primer, then sanded to the final shape. The end result was an excellent test model with nearly identical airflow characteristics and surface smoothness as the original model forebody.

The forebody model was reinforced internally with two 3/4-inch plywood bulkheads which were connected by internal wood frames on the right and left sides of the center of the fuselage (Figure 20). The bulkheads served as the model mounts where 1/2-inch steel pipes were bolted. The steel pipes were in turn bolted to a 3/4-inch plywood mount. The pipes provided about two feet of separation between the stand and the model (Figure 21).

The test stand was hinged to allow for variation in angle of attack, measured from the reference line of the upper edge of the LEX where it joins the fuselage, in order

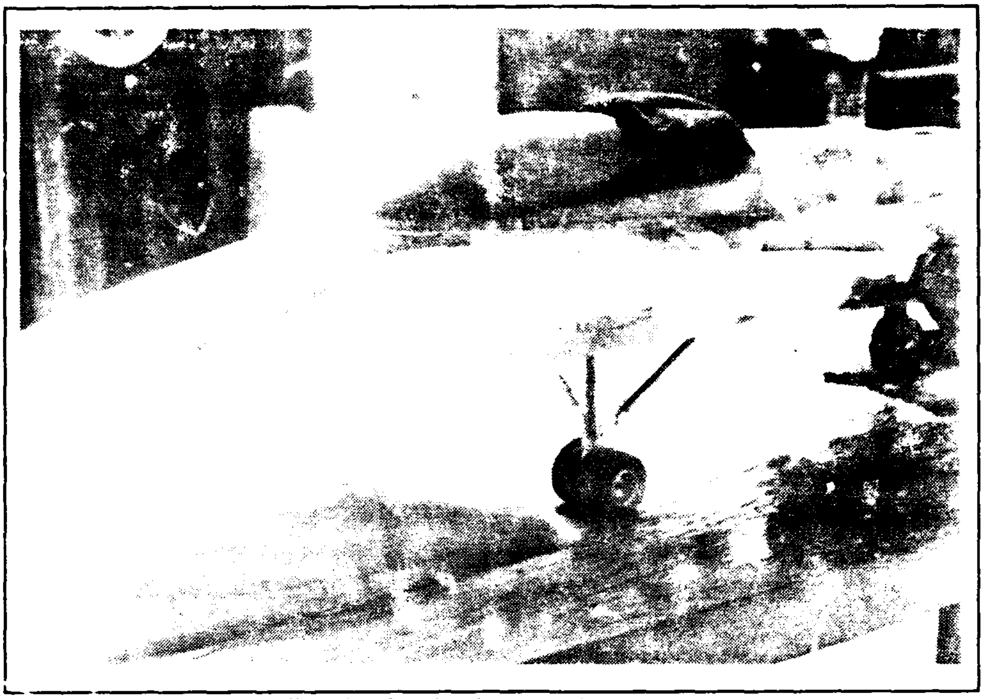


Figure 18 Upper molding for forebody model.

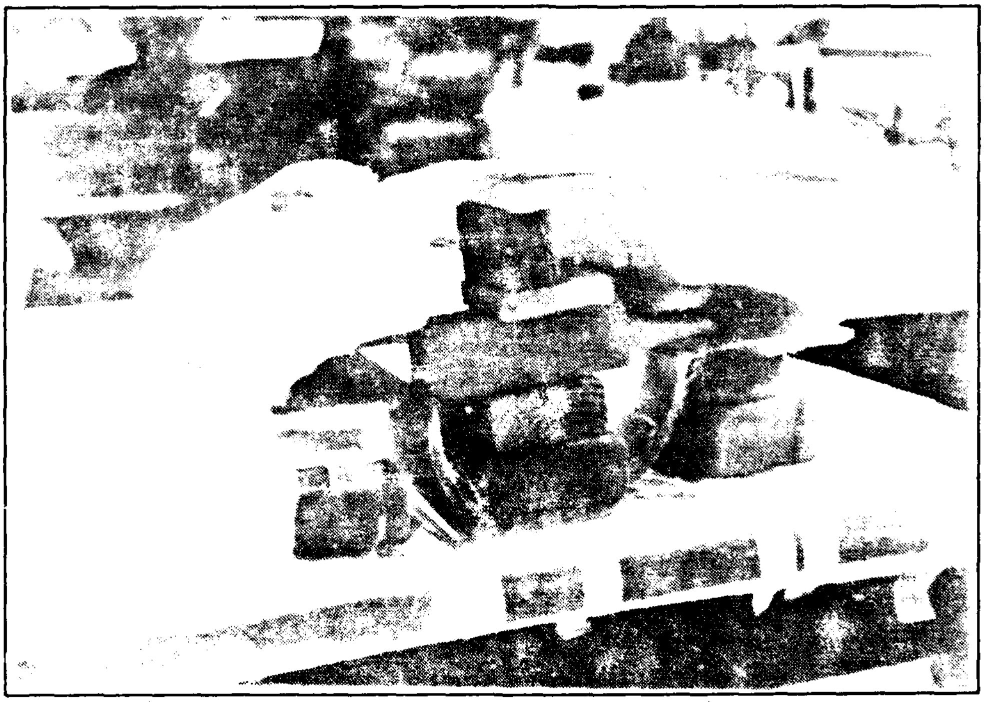


Figure 19 Rough forebody sections being joined together.

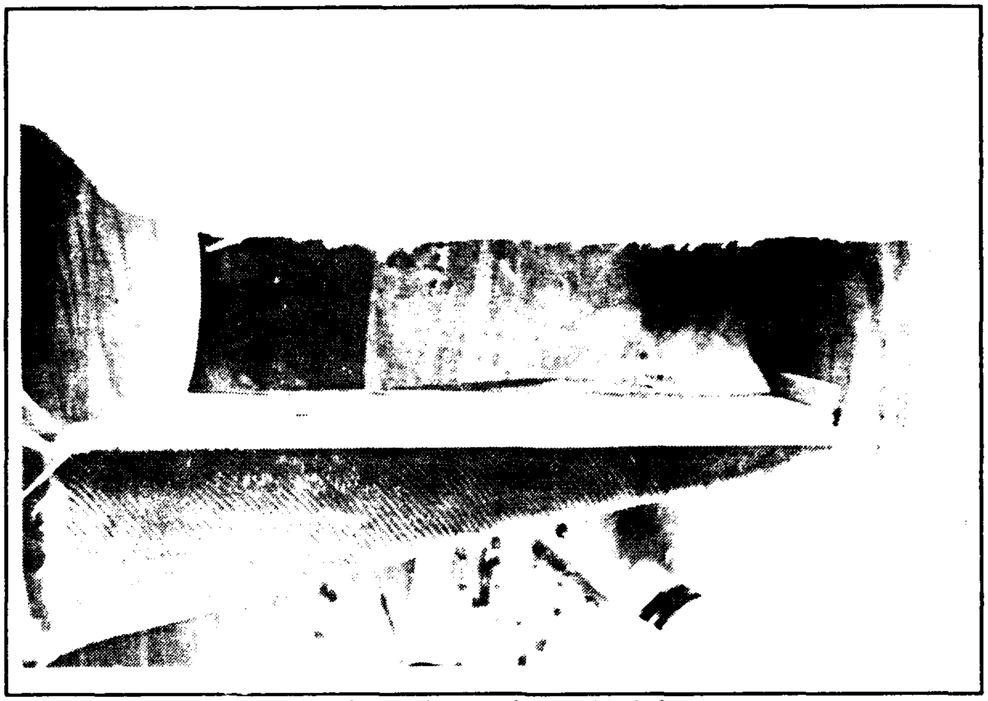


Figure 20 Forebody model with internal wood reinforcements.

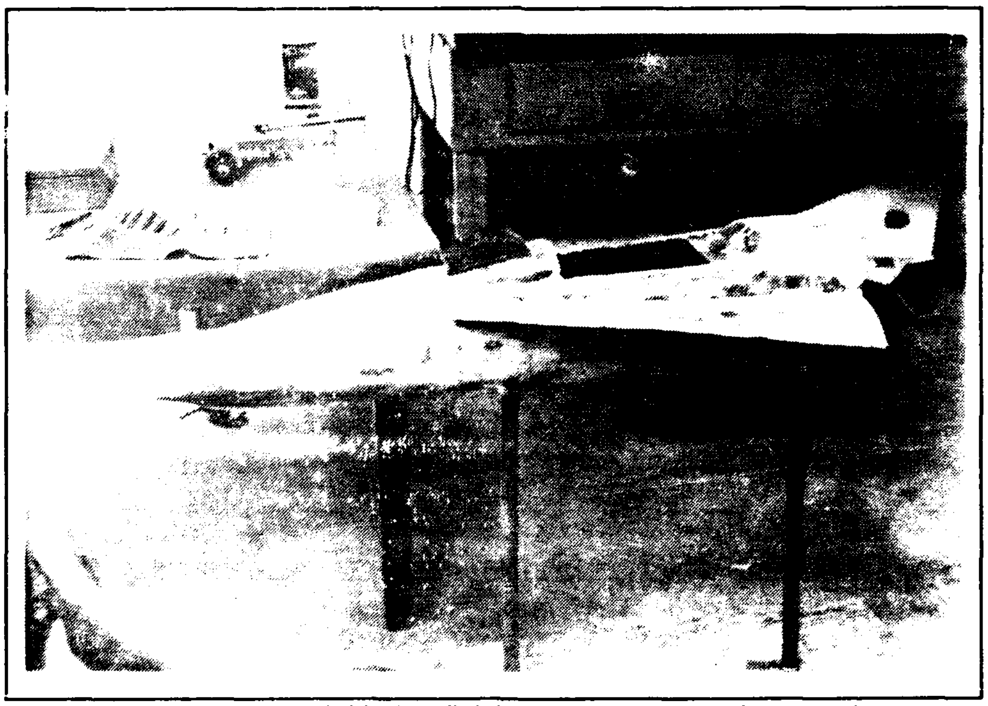
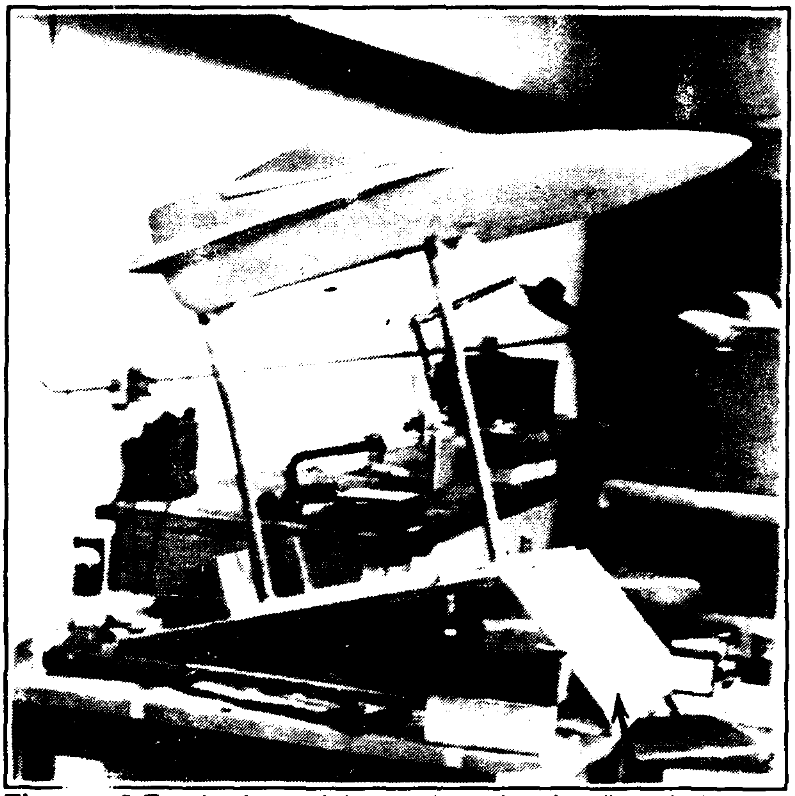


Figure 21 Forebody model being finished, mounted on pipe stand.

to simulate different flight regimes. An airflow deflector was also added to ensure air-loads would not damage the test model or automobile during the tests (Figure 22).



Figu :2 Forebody model at α=15°, showing flow deflector.

The system was tested by mounting the test stand to the top of a car (Figure 23). It was not the intent to achieve a full parachute deployment during these tests: there was not sufficient vertical distance. What was desired was to verify the effectiveness of the deployment system. Therefore, the parachute was not attached to the forebody model or automobile, but instead was attached to wood blocks lightly taped to the bumper of the automobile, which would separate from the car on deployment (Figure 24).

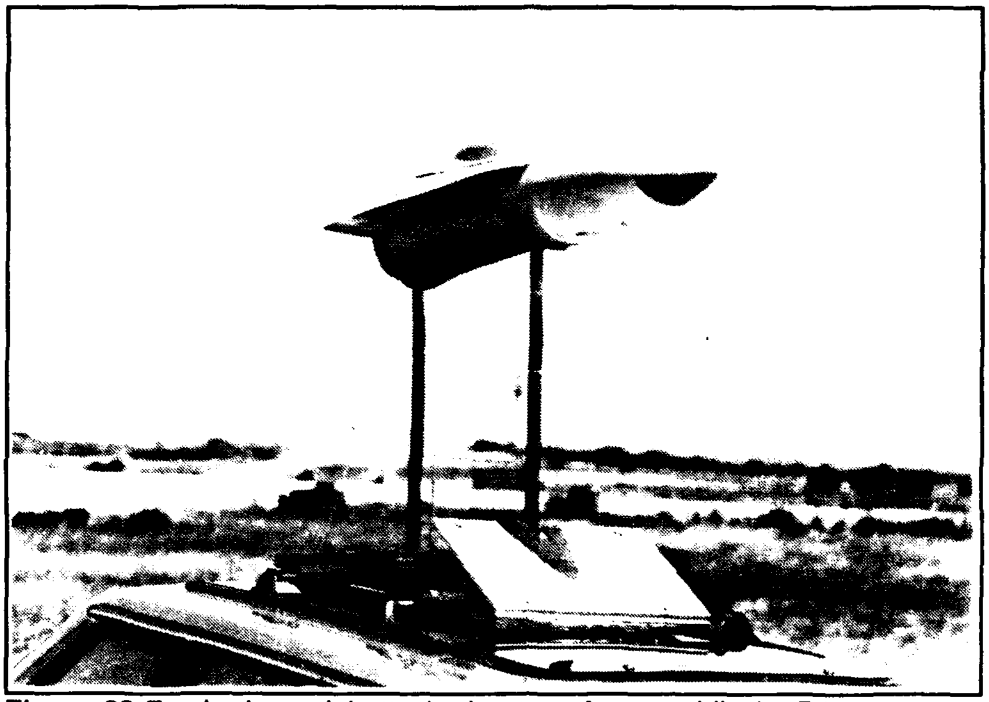


Figure 23 Forebody model attached to top of automobile (α=5°).

The tests were conducted on the Fritzsche Army Airfield 3000ft runway at Ft. Ord, California. This arrangement allowed for ample time to accelerate to the desired test speeds, and the ability to run two automobiles side-by-side for close visual observation. Two runs were made and the emergency recovery system was deployed at α = 5° at 60 mph and α = 15° at 48 mph. Video tapes were made of the deployments from two video cameras: one in the second automobile, and one from along side the runway.

The video tapes allowed for analysis of reaction times and deployment action. Since a motor-drive equipped 35mm camera was not available for the tests, still images were recorded by playing back the video tape on a 27-inch color monitor and photographing the desired frames, using a 35mm camera. Shutter speed were set at 1/60th of a second (in order to minimize the horizontal lines caused by the video refreshing blanker operating at 60 hertz).

Figure 24 Wood block arrangement.

For the low angle-of-attack test (α=5°), the deployment was rapid and clean. The springs popped the canopy up sufficiently, and then the aerodynamic loads rotated the canopy up and aft, extracting the parachute slightly up and aft rapidly, as the sequence in Figures 25 a 1 26 shows. Figure 27 shows the parachute fully extended and the wood blocks as the assembly slows to a stop on the runway.

The test run at α=15° was more dramatic. Due to the higher angle of attack, the aerodynamic loads were more effective. After the springs popped the canopy up into the freestream, the aerodynamic loads pulled the canopy up approximately an additional

Figure 25 Initial canopy separation (α=5°).

Figure 26 Canopy rotating up and aft (α=5°).

Figure 27 Parachute and wood blocks after deployment (α=5°).

4ft, as the sequence of frames shows in Figures 28 to 31. In Figures 32 and 33, it can be seen that the canopy falls aft of the projected fuselage, *extracting the parachute.*

Minimal damage was sustained by the canopy in the two tests, and on each test, the parachute was fully extended when retrieved from the run-way. Valuable information was gained by the two tests, namely:

- The dual servo initiation system was very reliable and effective at simultaneously releasing the forward and aft retaining pins.
- The spring forces were sufficient to achieve positive canopy separation but not so strong as to bind the retaining pins.
- In both tests, the canopy separation from the fuselage was adequate.
- The higher angles of attack at a slower speed provided better canopy separation from the fuselage.
- The aerodynamic loads on the canopy were sufficient to extract the parachute from the cockpit rapidly.

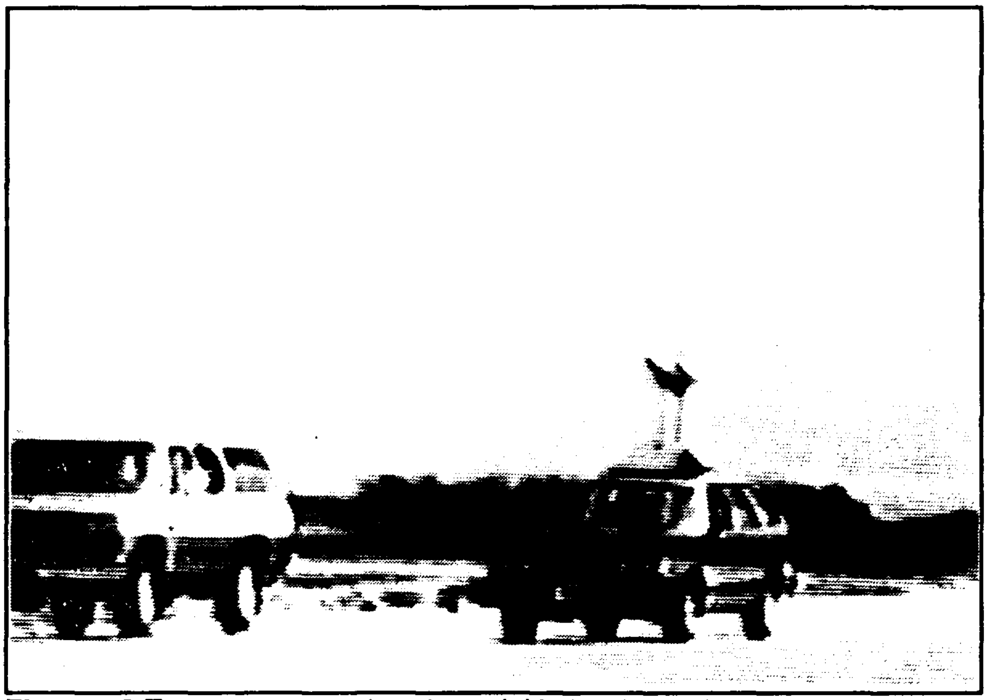


Figure 28 Test run at 48mph, prior to initiation (α=15°).

Figure 29 Spring ejection of canopy at release (α=15°).

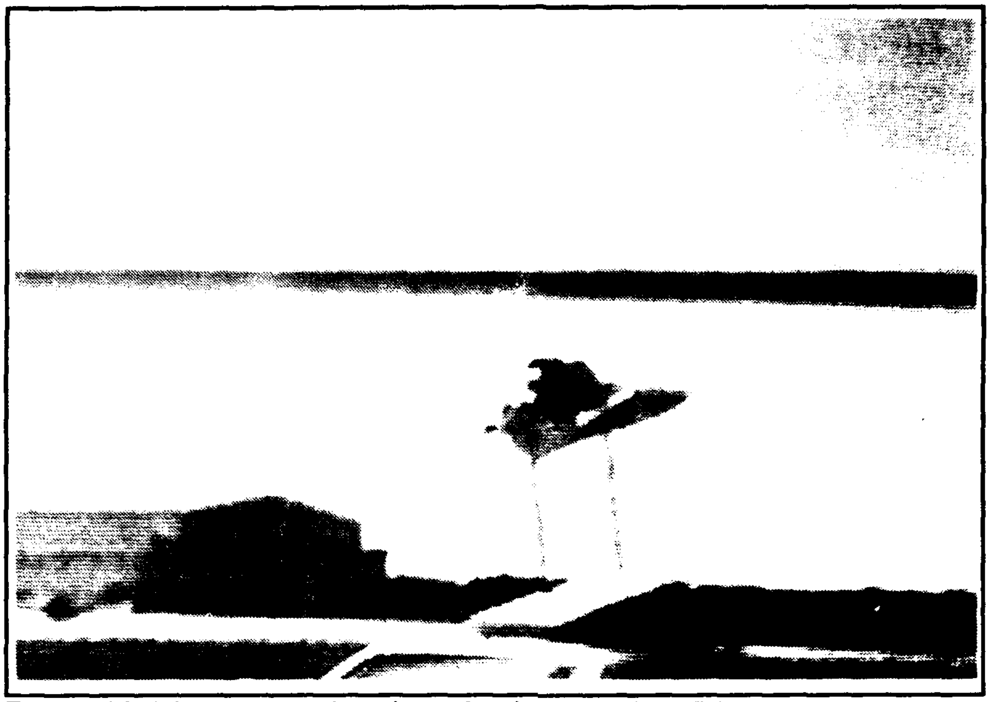


Figure 30 Adjacent car view, just after initiation (α=15°).

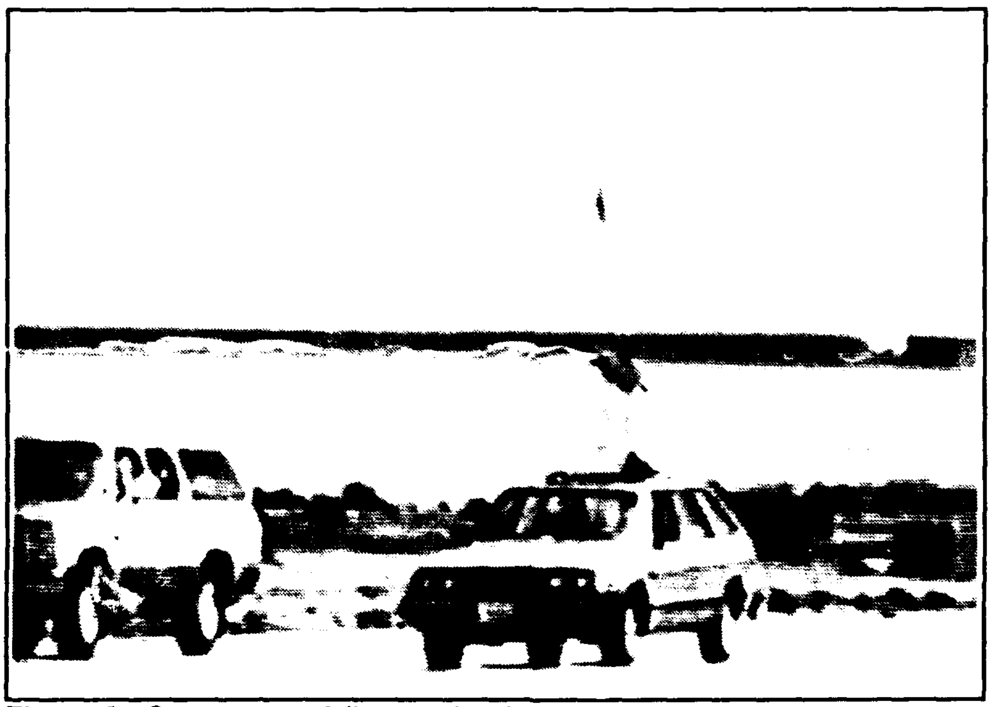


Figure 31 Canopy near full extension (α=15°).

Figure 32 Parachute in partial deployment (α=15°).

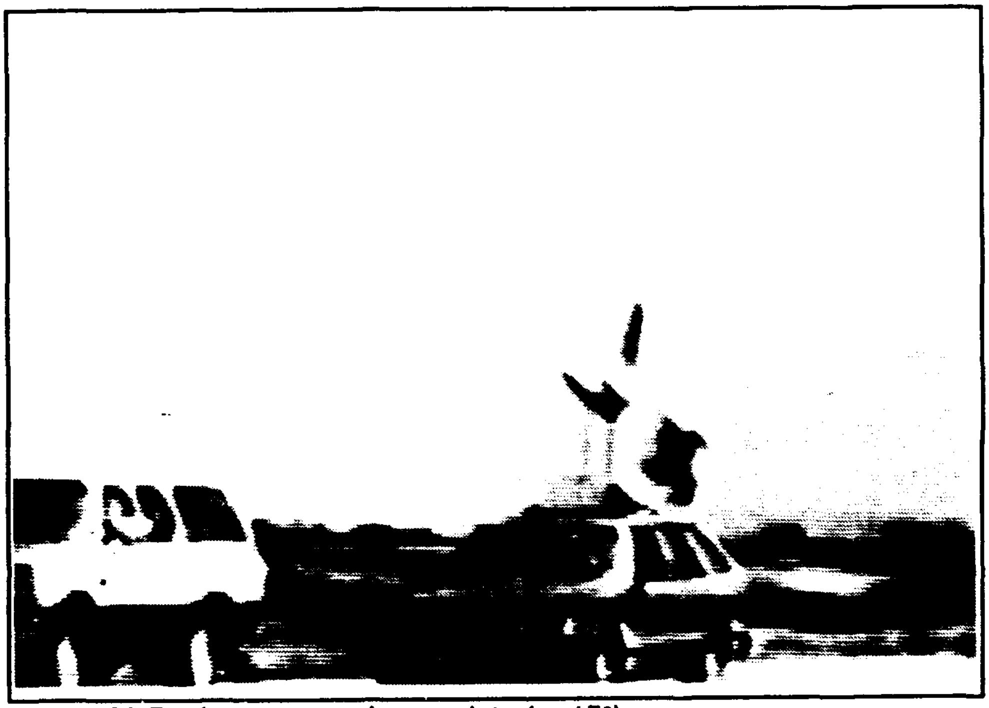


Figure 33 Deployment nearly complete (α=15°).

7. Testing of the Parachute

In order to verify that the required descent rate would be achieved, it was determined that drop tests would be required. A forty-foot repel tower was located at Ft. Ord that could be used for the drop tests. Exact repel tower measurements of horizontal markers were made and noted for the data reduction. All descent rates were based on a clearly defined 27.2ft reference line on the repel tower.

In order to simulate the drag of the aircraft in a vertical descent, a rough aircraft form was constructed with a 57x18-inch 3/4-inch plywood sheet and a 65-inch 4x4-inch beam. The 4x4-inch beam was cut down until a 31lb drop-test wood aircraft was achieved. The resulting wing-area was approximately 7ft^2, which was about 3ft^2 less than the *F-18* UAV.

Eight drop tests were conducted with the wood model, with the tests recorded on video camera. Figures 34 and 35 show the typical descent profile and repel tower. Data were reduced later by timing the steady state descent in a 27.2ft vertical drop. Fall times were typically slightly more than a second. In order to compensate for errors induced by stop-watch reaction times, five times were recorded for each drop, then averaged. Statistical methods such as Bayesian statistics, which would be able to take into account specific oscillation magnitudes and frequencies, wind conditions, and other effects for each drop (assuming proper modeling was applied), could have provided the maximum likelihood mean descent rate and the standard deviation. However, only crude approximations were required. Accuracy to within 1ft/s was considered acceptable, for no dynamic tests were conducted on the actual aircraft to determine the level of damage that could be expected at different descent rates. The 20ft/s criteria was based on an educated guess, with slight damage expected, but repairable.

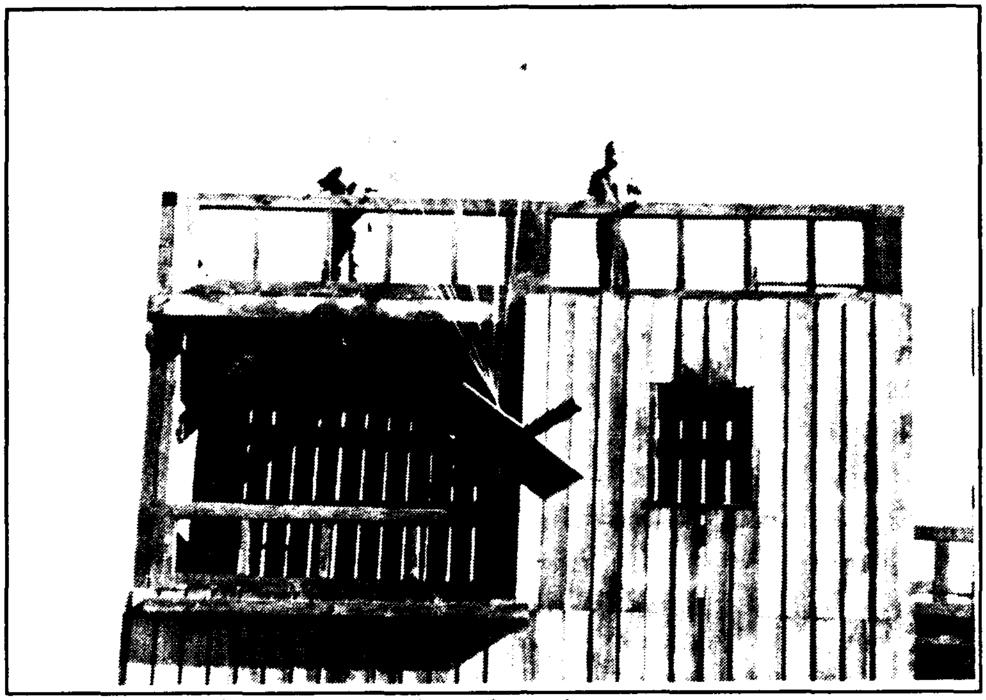


Figure 34 Parachute drop test, just after release.

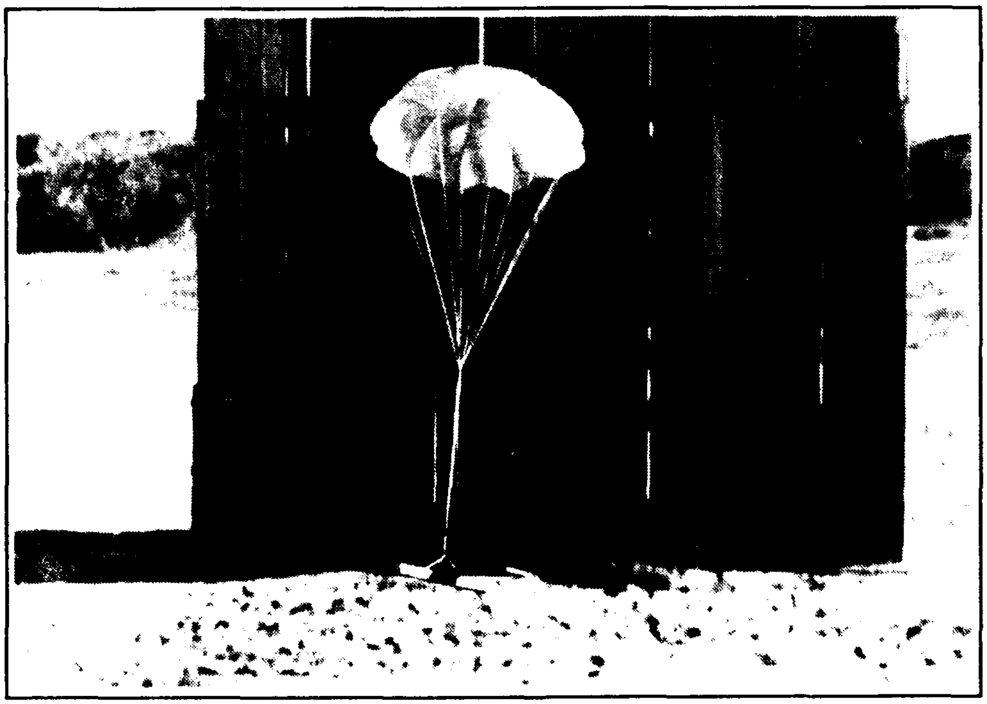


Figure 35 Parachute drop test, near impact.

It was found that with the stock parachute and a 31lb aircraft (with 3ft^2 less wing area), a descent rate of 22ft/s was achieved, which was outside of the design specifications. The parachute was then modified by a method called "pull-down apex" (PAD), which increases the C_D but causes an increase in the opening shock load factor. The apex was pulled down eight inches by a single line attached to the center of the apex and run down to the confluence point (where the suspension lines all converge).

Four additional drop tests were performed on the PDA-modified parachute, resulting in a decreased rate of descent of 20ft/s, as desired.

During two of the tests, the fiberglass canopy was attached to the apex with a 4ft lanyard. The fiberglass canopy did not appear to affect the descent of the parachute in any way, either visually or in the experimentally determined descent rates.

8. Recovery System Control Logic

The system design specification requires that the system be fail-safe. The design requires an internal logic circuit to react to an in-flight emergency, either autonomously or when commanded by the pilot, by deploying the emergency recovery system and concurrently shutting down the engines:

- If the aircraft enters uncontrolled flight and due to the aerodynamics of the aircraft or insufficient altitude, the pilot is unable to recover the aircraft.
- If structural failure occurs.
- If one engine fails and the other engine is unable to sustain level flight.
- If the control signal is lost for a predetermined amount of time.

Also, if at any time control authority is sufficient to "pull-up" and slow down the aircraft, and deploy the system at a higher angle of attack, the control logic should be programmed to perform the pull-up maneuver.

E. FUTURE GOALS FOR *F-18* PROJECT

As previously stated, the goal of this project has been to develop a generic fighter UAV to be used in flight test and ultimately to qualify supermaneuverability and agility concepts. It is anticipated that the project will require another year of development before these goals can be realized completely. Attention to detail and careful progress has been stressed throughout the construction and development of the F-18 UAV.

As guidelines for follow-on students, the following future stepping stones are provided.

1. Finish Construction

A major portion of the fuselage, wing, tail, and emergency recovery system have been completed. The next step is to complete the basic aircraft. Briefly, this entails installation of the rest of the servos, the fuel system, complete the gear door retract system, and installation of the radio and batteries. The wings and tail surfaces will need to be finished with a protective layer of fiberglass cloth before the hinges can be epoxied in place.

Finally, the aircraft surface will require finishing and painting in the standard NPGS UAV white and high-visibility orange color scheme, which ensures maximum visibility to the remote pilot.

2. Complete Initial Break-In Flights

Once the basic aircraft is finished, tests flights will be necessary to ensure all flight essential equipment is operating properly. At this stage, little instrumentation will be required, as the goal is to ensure a reliable platform is available for flight testing.

As with any initial flights, there will be higher risks until the bugs are worked out. It was therefore decided that the emergency recovery system must be fully functional before the first flight.

This stage is also very important for pilot training. For a successful test program, the pilot must have adequate experience in flying the basic model in normal flight modes before high angle-of-attack flight testing is conducted. This stage will include take-off, landing, stalls, and general pattern practice for the pilot.

3. Outfit with Complete Flight Test Package

Once a reliable test vehicle has been established, the instrumentation and telemetry additions must be completed.

a. Instrumentation

The type of information that will be required for the flight tests will include rudder, aileron, stabilator, and flap positions, airspeed, altitude, α, β, and engine rpm. Based on the lessons learned with the *PIONEER* and *F-16* UAVs, special potentiometers will be required for the control surface deflection measurements. The airspeed and altitude will be achieved with a simple, lightweight, pitot-static system. Proper calibration of each of the instruments must also be performed.

b. Telemetry and Recording

The *F-16* and *PIONEER* UAVs have undergone instrumentation and telemetry modifications and it is anticipated that similar systems will be used in the *F-18* UAV. Since the *F-16* UAV has undergone a complete telemetry package engineering and manufacturing cycle, it is desired not to duplicate this effort. A compact circuit-board designed for the *F-16* will either be borrowed for the *F-18* or a second one reproduced, specifically modified to add the second engine rpm and twin rudder information. Also, the multichannel ground recording station being developed for the *F-16* and *PIONEER* will be used for the *F-18* as well.

4. Complete flight tests

As with a full-scale aircraft, a complete flight test program will need to be completed. With the flight data of rudder, stabilator, aileron, and flap positions, airspeed, altitude, α, β, and engine rpm, a full set of flight tests can be completed in order to determine stability derivatives and performance characteristics, with emphasis on the determination of yaw control at high α.

5. Modify for Supermaneuverability Research

Once a complete set of static stability derivatives and performance characterizations is established, modifications of the aircraft can be made to introduce forebody control and thrust vectoring. Both qualification and some quantification of potential improvements can then be made. Although dynamic scaling is not directly applicable (otherwise the weight would be two orders of magnitude higher, requiring real turbojet engines, etc), the viability of control enhancement concepts can be investigated. Specifically, it is anticipated that two types of modification will be researched.

a. Forebody Control Modifications

Based on preliminary research conducted in the wind-tunnel, using forebody control surfaces to improve yaw control at high angles of attack [Ref. 29:p. 279], the incorporation of forebody control surfaces should be investigated.

There are several different types of forebody control that could be employed. The advantage of the generic fighter UAV is that the fiberglass fuselage can easily be modified. Also, the forebody model, which could be modified with a sting mount and forebody modifications and tested in a wind tunnel, could be used for the initial testing of controls.

One possibility would be to add spoiler-type, hinged surfaces which can be asymmetrically deployed and connected to the rudder control signals. Therefore, even though the rudders would be relatively ineffective at high angles of attack, the forebody control surfaces would be in clean flow, and when coupled with the long moment arm from the nose to the c.g., the net yawing moment improvements could be quite significant.

Another simple addition would be the incorporation of canards, again, added to determine the viability of the control enhancement concepts.

The NASA Ames Research Center has been investigating the effects of the injection of thin, high-momentum jets of air into the fuselage forebody boundary layer on yawing moments at high angles of attack on the F-18 aircraft using numerical methods [Ref. 30:p. 1]. It has been numerically found that one-sided blowing can result in strong asymmetrical flow patterns, causing a net lateral force. The blowing, if controlled, could provide needed yaw control at high angles of attack, when the rudders are ineffective. Similar to the forebody control surface modification, incorporation of a blowing system would be simple with the *F-18* UAV through the use of compressed-air bottles like those used for the pneumatic landing gear system. A single servo, connected to the rudder channel, could control the asymmetric blowing. Again, coupled with the long moment arm, the net yaw control improvement could be significant.

The *F-18* UAV would be an ideal research vehicle to verify these concepts. Given that the complete flight test instrumentation package is installed, flight tests in high angle-of-attack flight will be performed and improvements in yaw control will be qualified.

b. Thrust-Vectoring Modifications

Again, one of the very strong points of using UAVs for flight research is the ease of modification. Adding a thrust-vectoring modification through servo-actuated thrust deflectors in the area of the tailpipes would be relatively simple. The tailpipes exhaust very near to the furthest aft location on the aircraft, so small net lateral forces could result in significant net yawing moments. Also, since the tailpipe exhaust temperature is very close to ambient temperature, no special materials would be required for the thrust-vectoring nozzles.

V. PARACHUTE INTEGRATION INTO OTHER NPGS UAV PROJECTS

The more expensive the aircraft and the more risky the flight testing being performed, the more likely an emergency recovery system will be necessary. One would not likely want to put a $500 emergency recovery system on a $300 to $500 model, unless the model was extremely difficult and time consuming to build. One would also not want to add a bulky and heavy emergency recovery system on a UAV that is already underpowered or aerodynamically sluggish.

For each of the current projects, an analysis, considering factors such as risk, cost, weight, performance, and mission, should be conducted in order to determine if an emergency recovery system is needed. If one is needed, the procedures outlined in sub-section C of Chapter IV should be reviewed.

The Appendix contains more details on parachute characteristics, design parameters, and guidance for parachute selection.

Also, although a mechanical system was used for the emergency recovery system initiation for the *F-18* UAV, other options exist, with a variety of performance and cost trade-offs. If very rapid deployment were considered essential, the ballistically fired system might be required, at an additional expense and weight penalty.

VI. CONCLUSIONS AND RECOMMENDATIONS

The *F-18* generic fighter UAV project was initiated and construction is near completion. Many engineering challenges were presented along the course of construction. Also, the vital emergency recovery system has been designed, constructed, and thoroughly tested. It is felt that the system will provide a reliable and effective safeguard against inadvertent loss of the aircraft. This will allow a more aggressive testing program to be conducted, without the fear of losing the aircraft in high angle-of-attack flight research. The project promises to be a valuable tool in the investigation of supermaneuverability and agility research, which can be easily and cost-effectively modified.

The forebody model can be used for future research, including wind tunnel tests with forebody modifications and further emergency recovery system deployment engineering.

Two additional students, following consecutively, have been recruited to follow the project through to completion.

The insight provided by the supermaneuverability and agility research conducted by the UAV facility should indicate the direction of further research efforts, to be conducted in manned aircraft research with such vehicles as the NASA High Angle-of-Attack Research Vehicle (HARV).

APPENDIX - PARACHUTE DESIGN SUPPLEMENT

The Recovery System Design Guide is used by the military as well as industry and covers virtually all types and uses of aerodynamic decelerators, including those used for air vehicle normal and emergency recovery, airdrop of material and personnel, aircraft deceleration and spin recovery, ordnance deceleration, aerial pickup, and other special uses. Decelerator characteristics, components, subsystems, materials, construction details, testing, performance, and design are covered, as well as analytical methods for predicting system motion, deployment impact loads, opening shock, stress analysis, stability, landing dynamics, and reliability. This appendix is included in order to share some additional material on parachute integration as it applied to this thesis project. For a more complete coverage of the subject, reference 25 should be consulted.

A. PARACHUTE CHARACTERISTICS

Briefly, some of the parachute characteristics should be covered, such as specific terminology, characteristic dimensions, and performance parameters.

The parachute canopy is usually made by sewing several specially cut pieces of fabric, called gores, together. How the gores are cut determines the shape of the parachute. In the 10-gore flat-circular parachute used for the F-18 UAV, each gore is triangular, with a gore angle of 360/10=36°. Modification to the basic triangular gore are typically done to decrease hoop stress, particularly in the mid-crown region, which also adds fullness.

A reference area S_O is defined as the nominal surface area of the canopy constructed surface area (the surface area of the fabric), to include the vent, slots and other openings within the gore outline. Once S_O is known, the nominal diameter D_O is calculated as:

$$D_O = \sqrt{\frac{4S_O}{\pi}}$$

The constructed dimension called D_C is the diameter of the canopy measured between points of maximum width of opposing gores.

A fabric parachute has a different shape when it is inflated than when it is constructed due to the stretching of the fabric during inflation. When aerodynamically loaded, the canopy typically forms a concave scalloped shape. A projected area, S_p, is the second common parachute area, and is used to determine the projected diameter D_p. These two values are used in the ratios of S_p/S_o and D_p/D_o, which are important decelerator parameters.

Another important design parameter is the l_e/D_o ratio, where l_e is the effective length of the suspension lines and influences the shape and projected area of an inflated canopy.

To compare the opening shock characteristic of a parachute design, the opening load factor, C_x, is used. It is a ratio of the peak opening force with a infinite mass (no deceleration allowed) to the steady state drag force during inflation at a constant flow velocity. Ideally, the ratio should be close to unity, and through canopy growth control by reefing, the opening shock can be minimized. The flat-circular parachute used in this project had a C_x = 1.8, with no reefing.

Another important characteristic of a decelerator is the stability, measured by the average angle of oscillation. Table 1 is given to show a representative sample of some of the parameters discussed above.

TYPE	D_c/D_o	D_p/D_o	C_{Do}	C_X	Angle of Oscillation
Flat Circular	1.00	.67-.70	.75-.90	1.8	10-40 degrees
Conical	.93-.95	.70	.75-.90	1.8	10-30 degrees
Bi-Conical	.90-.95	.70	.75-.92	1.8	10-30 degrees
Hemispherical	.71	.66	.62-.77	1.6	10-15 degrees
Annual	1.04	.94	.95-1.00	1.4	less than 6 degrees
Cross	1.15-1.19	.66-.72	.60-.78	1.2	0-3 degrees

Table 1 Typical Parachute Performance.

B. APPLICATION TO THE F-18 UAV PROJECT

For this thesis, according to Table 1, the expected performance of the flat-circular parachute was a C_{Do} of 0.8 and a stability of an average angle of oscillation up to ±40°. The canopy was carefully measured and a S_o of $48ft^2$ was found. Based on the test drops, a C_{Do} =1.1 was achieved for the basic parachute and a C_{Do} = 1.3 for the PDA modified parachute. The most probable explanation for the differences in the coefficient of drag is that the wooden aircraft provided a significant amount of drag, or that the 40ft tower did not provide a sufficient vertical drop for the tests. It is likely that the wooden aircraft was accelerating throughout the drop and that the terminal velocity had not yet been reached.

Other options were considered for the test drops. Either a helicopter drop or a hot-air balloon drop from 2000ft would have been much better, but were not feasible.

Based on the information gleaned from the design guide, perhaps a better choice would have been to use the cross parachute. Although the coefficient of drag is typically lower than for a flat-circular canopy, the opening load factor is much better and the stability is excellent. In that the parachute accounts for only about 35% of the weight of the emergency recovery system, a larger cross parachute would not have been significantly heavier, as shown next.

An expert in the field of parachute design was consulted [Ref. 28], and based on empirical data, a e_s/D_c ratio of 0.31 provides the best performance, where e_s is the width, measured perpendicular to the suspension lines. Therefore $S_o = 2e_sD_c - e_s^2$. Assuming that a $C_{Do} = .78$ can be achieved, and a 20ft/s rate of descent is desired, the required S_o would be $81ft^2$. At 1.1 oz/yd^2, this would equate to a 0.62lb parachute, an increase of only 0.19lb. Taking this reasoning one step further, if it were desired to reduce the rate of descent to 15ft/s, the required S_o would be $144ft_2$, with a 1.1lb parachute. Obviously, to decrease the rate of descent by 25% requires a parachute which weighs twice as much.

C. RECOMMENDATION

Therefore, based on the above analysis, it is advised that a cross parachute be ordered for the F-18 UAV, based on a $C_D = 0.78$ and a descent rate of 20ft/s, in order to gain the advantages of stability and less opening shock. Although the weight of the parachute will increase 1/5th of a pound, all the other hardware requirements in the system will remain the same, with a net increase of the total system weight of only 1/5th of a pound.

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